
OPERATIONAL EFFECTIVENESS
OF
UNMANNED UNDERWATER SYSTEMS
MARINE TECHNOLOGY SOCIETY
ROV COMMITTEE
DREW MICHEL CHAIRMAN
EDITED BY ROBERT L. WERNLI
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FOREWORD

The Foreword of the "**Operational Effectiveness of Unmanned Underwater Systems"** is provided as a video presentation by Drew Michel, Chairman of the Marine Technology Society committee on Remotely Operated Vehicles. CLICK HERE

PREFACE

This publication has been produced to provide guidance and information to those who use, plan to use, or are just interested in unmanned underwater systems and their associated technology. It is based on the original MTS publication "Operational Guidelines for Remotely Operated Vehicles," which I had the pleasure of producing during 1983-1984 with the late ROV expert R. Frank Busby and a cast of experts from, at that time, this fledgling industry. But, unlike the original publication, this is not a "guideline." It is a discussion of the systems and what can be expected of them. In essence, it will tell you what they are, what they can and cannot do, where they are operating and how successful they are, what you should be aware of and what can be expected in the future. It will provide you with an understanding of the "operational effectiveness of unmanned underwater systems."

In 1984, MTS published the original "ROV guidelines" to fill a void that existed on the topic. Since then, several other publications have been produced–mostly in Europe, and mostly addressing operations in that geographical region. They provide more detailed points for operators, technicians, and the basic user. It is not our intent to produce a similar publication, but provide them as references in the bibliography. Nor, do we plan to reproduce our original guidelines, although some of the more pertinent material has been updated and retained. This publication will do what they do not–address what is necessary in general–a real international understanding of the usefulness of these fantastic systems. And with that point in mind, we have produced the first version of this publication as a CD ROM, with hypertext links from key words in the basic text to material. The goal is to provide you with a truly interactive publication that will provide the necessary information accurately and quickly. The following paragraphs will discuss the organization of this publication and where important information can be found.

Chapter 1 - What Are They? - will provide the obligatory introduction of the industry to include a basic history lesson. It will then go into the next level of detail on the classes of systems in the industry and what their basic ranges of applications are. Examples are provided of all system classes.

Chapter 2 - What Can They Do? - addresses the general tasks that the systems are doing in the commercial, military, academic and related communities.

Chapter 3 - What Can't They Do? - will provide something that is usually lacking; that is a basic understanding of the relationships between the key operational parameters of the systems and what they can be expected to accomplish. Such issues as speed, range, navigation, search, work, stealth, etc. will be addressed. In plain language, it will tell you how to cut through the sales pitch blarney and know what you are really getting–or can get.

Chapter 4 - Where Are They Doing It? - is self explanatory. The technology has expanded from it embryonic start in the Gulf of Mexico, through the Pacific coast and the North Sea and is now used world wide, including the poles. The extent of this usage will be covered in this chapter.

Chapter 5 - How Successful Are They? - will cut to the chase and address their reliability, cost effectiveness, safety and potential to replace divers and submersibles. A “no blarney” discussion of the real parameters of success.

Chapter 6 - What Should I Know About? - takes you from the system to the subsystem level. The information you should have at your fingertips to understand the subsystems AND the technology. And, with the hypertext links to examples and items of interest, we’ll be able to follow the old adage–Show, don’t tell.

Chapter 7 - Operational Considerations - continues the words to the wise provided in Chapter 6 with information on platforms, mobilization, safety, training, legal and environmental considerations.

Chapter 8 - What Will They Do In The Future? - lets us put on our wizard’s hats and project where the technology and the systems will go in the future. Not just another blue sky projection of solving the world’s problems, but a realistic look at what will be available, and when, for you to plan your strategy of staying one up on the competition.

Appendices–In addition, the Appendices are full of useful information. And, if it isn’t in this publication, references on where you can find the information are provided.

The Marine Technology Society has provided an international forum for the exchange of technical information on unmanned underwater systems for several decades. I assumed the chairmanship of the MTS ROV Committee from Drew Michel in 1981, and with the support of experts in the field, we began the ROV conference series in 1983. As Chairman of the ROV conferences for ten years – 1983 through 1992 – I had the privledge of working within an area of technology that is the most exciting on Earth, and doing so with an outstanding group of international peers. In 1993, Drew Michel took the ROV Committee reins once again and has co-chaired the Underwater Intervention conference series since. For 16 years the conferences have provided an international networking capability for experts from around the world, and it is to all of you who have spent your careers advancing this exciting technological area that this publication is dedicated. And, to those just entering the field, who will learn from our past failures and successes and carry the baton in the future. Whether novice or expert, our goal is to provide a publication that will ensure a full understanding of the **“Operational Effectiveness of Unmanned Underwater Systems**.”

Robert L. Wernli
Editor and Co-Author

OPERATIONAL EFFECTIVENESS
OF
UNMANNED UNDERWATER SYSTEMS

A Project of the ROV Committee of the Marine Technology Society
Drew Michel, Committee Chairman

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This publication is not presented as a set of standards, but as a compendium of information relating to the status of unmanned undersea vehicles around the world. Any discussions or descriptions of systems, subsystems and their operation are provided as guidelines for those working or interested in the field of unmanned underwater vehicles. This publication is not presented as a set of standards. No other use is intended or implied. Mention of a commercial product does not constitute an endorsement of that product by the Marine Technology Society.

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Drew Michel
ROV Committee Chairman

LIST OF FIGURES AND CREDITS

The following list of figures is provided to allow easy cross reference and location of specific items and to acknowledge those (shown in parentheses) who provided the wealth of excellent material contained herein. Abbreviations used in the following list include:

DOE – Deep Ocean Engineering
DSSI – Deep Sea Systems International
FAU – Florida Atlantic University
HBOI – Harbor Branch Oceanographic Institution, Inc.
JAMSTEC – Japan Marine Science and Technology Center
MBARI – Monterey Bay Aquarium Research Institute
MIT – Massachusetts Institute of Technology
MTS – Marine Technology Society
NPS – Naval Postgraduate School
ROS – Remote Ocean Systems
SAIC – Science Applications International Corporation
TSC – Technology Systems Corporation
WHOI – Woods Hole Oceanographic Institution

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Williamson & Associates Inc.'s coring system with thrusters (TSC)
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Trail Blazer (International Submarine Engineering, Ltd.)
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CHAPTER 1. WHAT ARE THEY?

HISTORY

Introduction

Prior to discussing the life story of unmanned underwater systems, a few words regarding terminology are warranted. You may ask "Why are the authors using the term ‘unmanned underwater systems’ for the title?" Good question–here’s the rationale. When MTS first published the book "Operational Guidelines for Remotely Operated Vehicles," there was nothing on the market at that time that addressed the problems of using such systems; and, they were rather unique–far from the diverse spectrum of systems now available. When the tether began to be eliminated, the term for "untethered" vehicles began to appear, which eventually became autonomous, semi-autonomous, etc. The definition of such systems actually became a small battleground between several leaders in the industry–was an autonomous (or semi-autonomous) system actually remotely operated, and thus an ROV? Frank Busby in his publications, which set the standard in the industry, classified everything as an ROV. Under that were several sub-classes that covered everything from bottom crawlers through structurally reliant systems, and eventually to autonomous vehicles. After all, at that time, nothing was truly autonomous (and essentially still is not), with man always somewhere in the loop either communicating via an acoustic link, fiber optic cable, radio control, or with preprogrammed routines. And, the semantic battle still continues between the old guard with the ROV classification and many academics that insist their systems are truly "autonomous."

Adding to the confusion, or should we say complexity of terminology, is Hydro Product’s RCV line, the Benthos *RPV-430*, and the more recent term adopted by the US Navy–Unmanned Undersea Vehicles–UUVs. Actually, it is a good term, however, it connotes military applications, and although could cover the field, it isn’t universally accepted as the all-inclusive acronym for such robotic systems.

Now, bring on the LCROVs–Low Cost ROVs (add a "V" and you get Very low cost). These little guys were originally classified as being under $50K in total system cost and were relatively portable (add the V and you drop the price to around $10K or less). This miniaturization is a good example of the technology breakthroughs being made in the industry. This term has been fairly well received around the industry, however, the debate will likely expand regarding LCAUVs as the academic community advances the field toward smaller and cheaper autonomous vehicles. And, in the extreme, are all the systems discussed really vehicles? Thus, the question of which term to choose: ROV, AUV, UUV, RCV, RPV, LCROV, VLCROV, LCAUV... And, they are not just “undersea” vehicles, they are working the inland waters at an ever increasing pace. Thus, our decision to go with a new, generic title for this publication–Unmanned Underwater Systems–that encompasses all of the above.

We will, however, strive to adapt some conventions that have evolved over the past decades: ROVs will primarily pertain to tethered systems, including expendable fiber optic tethers; AUVs will deal with untethered systems, to include non-tethered communication links such as acoustics; UUVs will remain with the US Navy and the military; LCROVs will remain inexpensive vehicles as previously defined; the towed, bottom crawlers and hybrids will be dealt with individually, in the clearest fashion possible.

Now that we have set the stage for the discussion to follow, let us continue with the history of unmanned underwater systems. ROVs will be dealt with first, followed by AUVs, and then the remaining systems, which include bottom-crawlers/towed systems, hybrids and towed mid-water vehicles. The towed mid-water vehicles, although ROVs with limited capability, will be dealt with separately since their advancement is primarily tied to the sensors they carry–and although they were probably here first, they'll be addressed last.

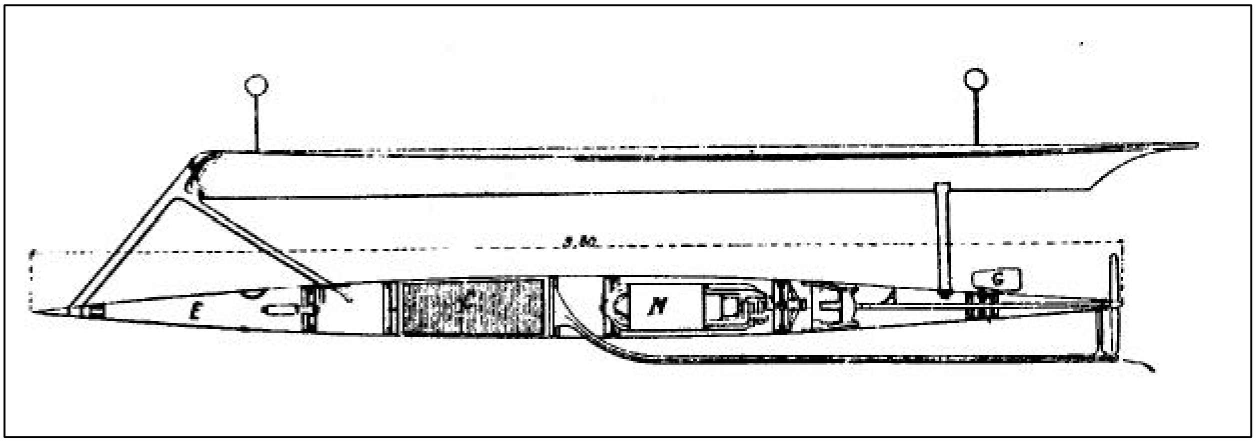
There are several ways to approach such a historical discussion, however, placing ROV development into terms of human progression seems quite appropriate for two reasons: the titles adequately reflect the phases of the industry, and everyone can identify with the analogous problems of raising a child through the various stages of ones life, from infancy to maturity–when they can finally become "autonomous" and leave home on their own...or do they?

The Creation of an ROV Industry

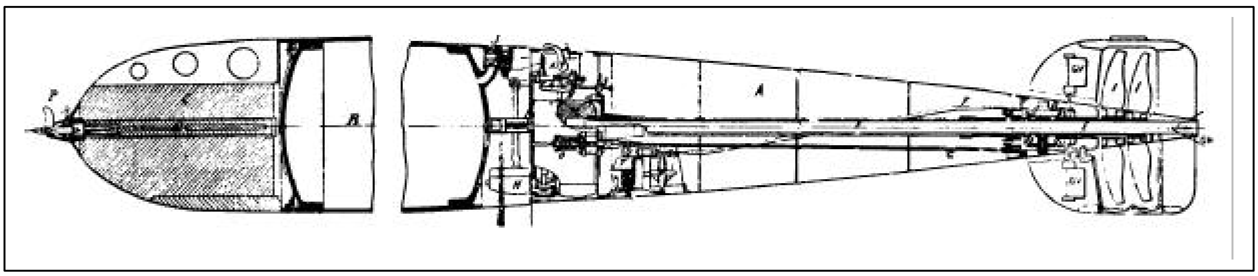
Infancy (1953-1965)

The first question asked when you have to deal with a "new bouncing baby" is "who's the father." Strange, in the beginning, no one really cared–the child was ugly and nothing but a problem: their bottles leaked, their hydraulics failed, sunlight damaged them, they were too noisy and unreliable, were hard to control and needed constant maintenance. Beginning to sound familiar? Well, we have to lay the blame on someone, so here is our best shot.

Frank Busby felt the first ROV was probably built by Dimitri Rebikoff in 1953. Called the *POODLE*, it was a modified version of Rebikoff's diver transport vehicle *PEGASUS*. Used primarily for archeological research, *POODLE's* initial impact on the underwater scene was minimal. The fault was not due to any inherent weakness or deficiencies in the vehicle's design or performance; it was an idea whose time had simply not yet arrived. This was a time when the industry was enamored with man's assault on the oceans, and at that time, it required man to be there to do the job. The child remained fatherless. Quite the gentleman, Rebikoff gives credit to the *PUV* (Programmed Underwater Vehicle) Luppis-Whitehead Automobile torpedo developed in Fiume (then in Austria) in 1864. This was followed by the first wire-controlled torpedo co-invented by Sims/Edison in 1891. Figures of these early vehicles are shown on the following page.



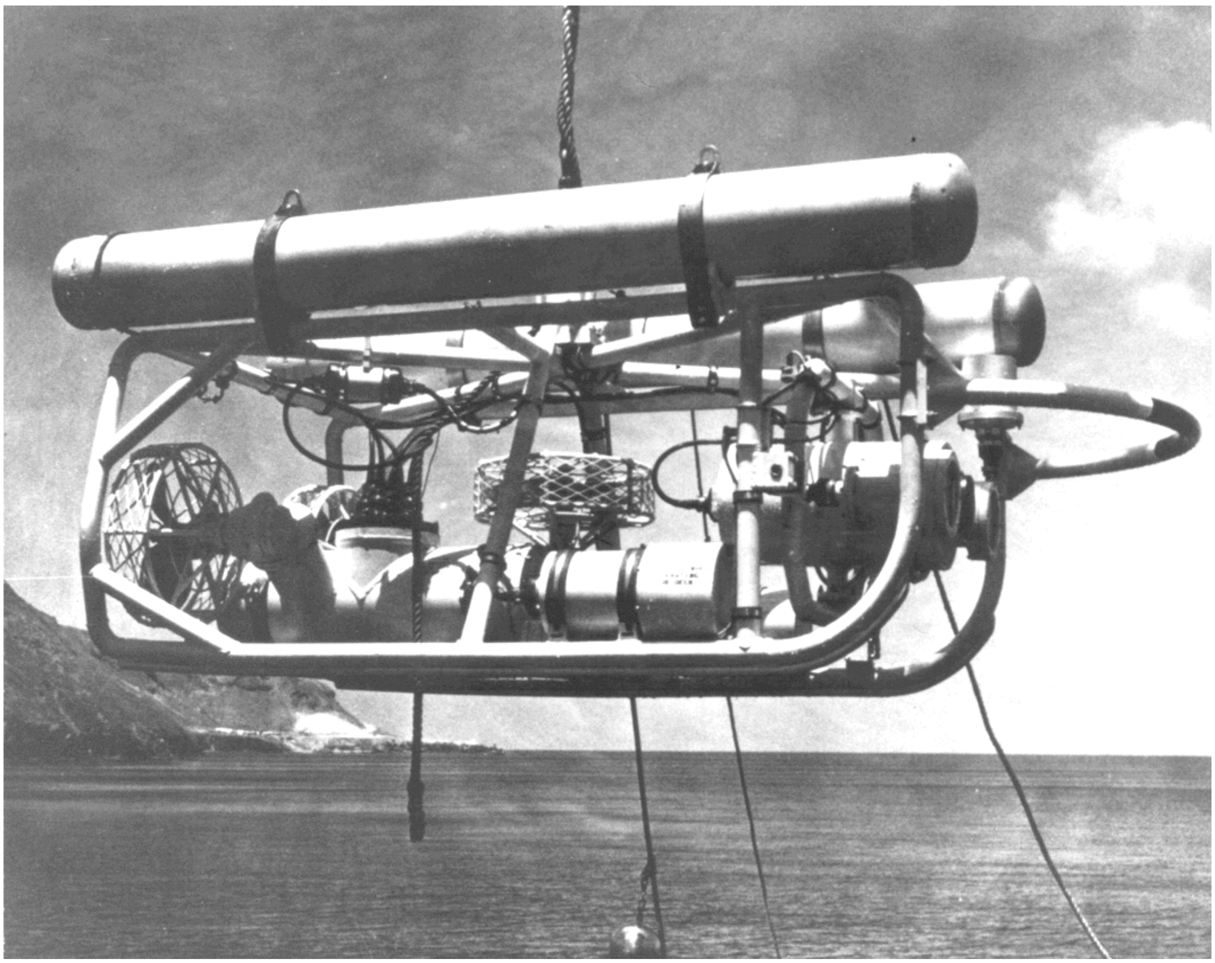
The Sims-Edison Torpedo



The Whitehead PUV/Torpedo

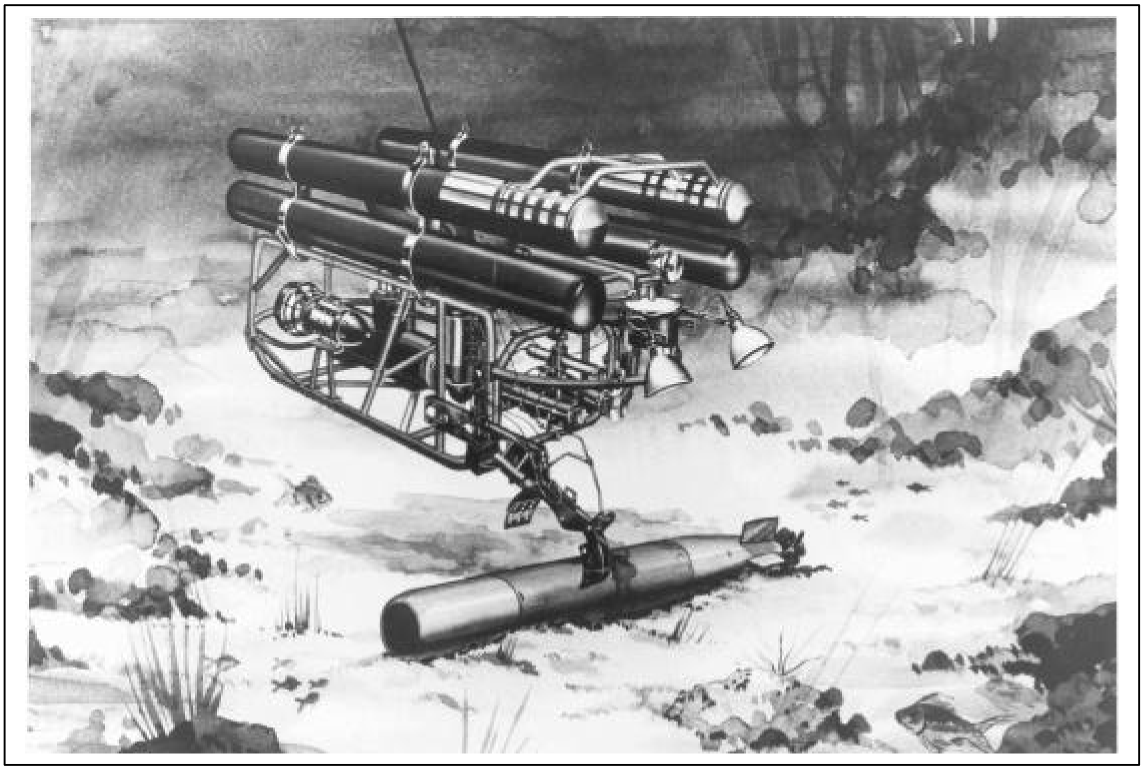
Now, these systems were far ahead of their time, but do not quite fit the ROV category. The late Dr. William "Bill" McLean, an avid ROV supporter, developed the Sidewinder missile, but it is not considered the father of UAVs–Unmanned Aerial Vehicles–the military's flying equivalent to UUVs. So, for this publication, torpedoes will not be treated as ROVs/AUVs any more than missiles are considered UAVs.

At about the same time Rebikoff was developing the *POODLE*, the US Navy was trying to come up with a more efficient method for recovering lost ordnance from the sea floor. With the development and use of underwater cameras, the method for finding the target was to moor a vessel in the area and move or drag a tripod, which carried the camera on a pan and tilt, along the sea floor. Needless to say, grappling was an inefficient and painstaking way to recover a lost object–but it did work. A method of reducing this inefficiency is attributed to J.R.R. (Bob) Harter, with the then Navy Bureau of Ships, who contracted with VARE Industries, Roselle, New Jersey, to develop a maneuverable underwater camera system–a Mobile Underwater Vehicle System. Several units were built, with varying degrees of success, until a working unit–Serial No. six–was delivered to the Naval Ordnance Test Station (NOTS) in Pasadena, California, in 1961. Called the VARE vehicle (see figure below), or *XN-3*, it was equipped with a clamshell claw and operated by the Navy laboratory. Unfortunately, the vehicle was unreliable and just too much trouble, so it was stripped down to the bare frame by the laboratory and redesigned.



Original VARE Vehicle

Following the metamorphosis, the Cable-Controlled Underwater Research Vehicle (*CURV*), see figure below, was unveiled–the child had been adopted.

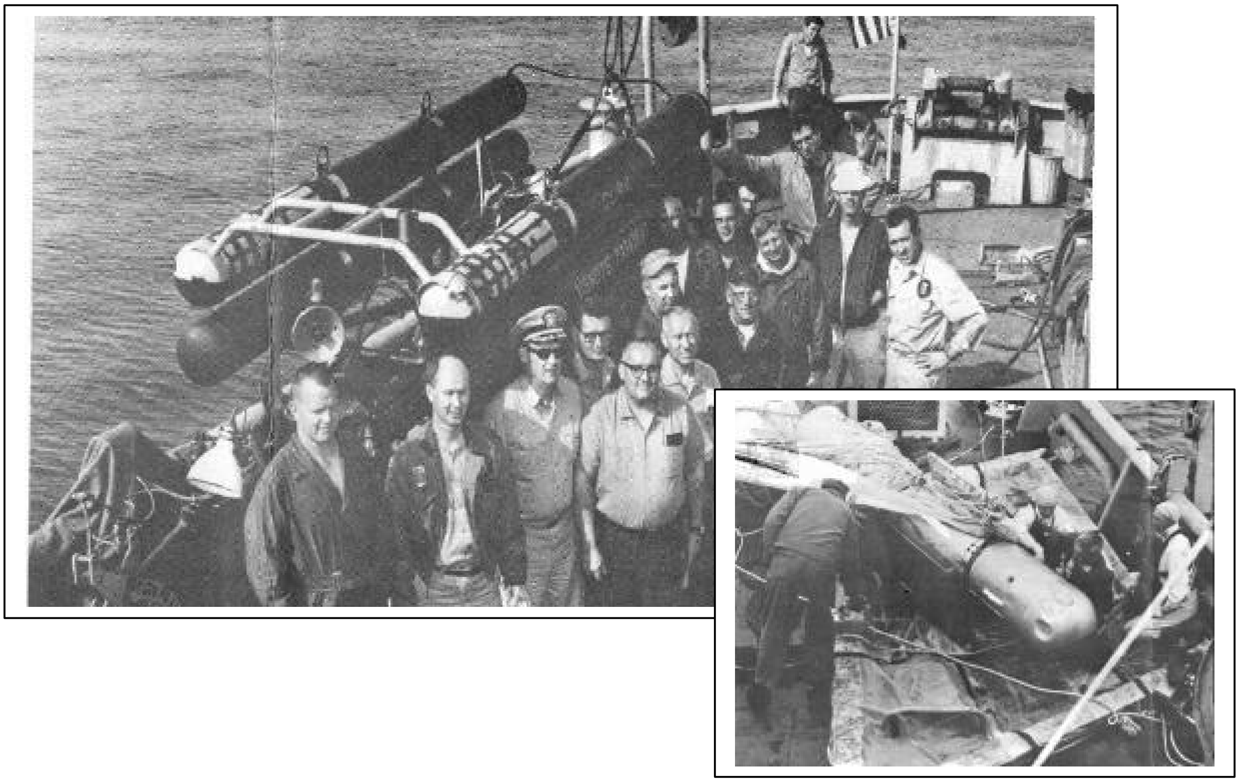


Artist's Rendition of US Navy's *CURV I*

Childhood (1966-1974)

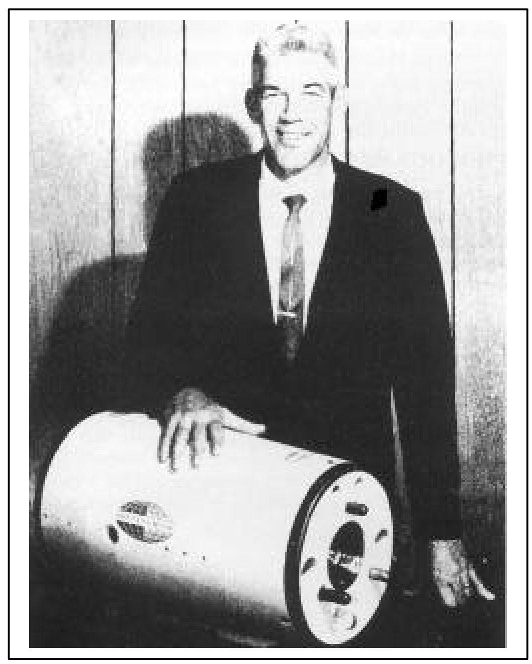
The *CURV* had no sooner joined the cast when it took center stage during the US Navy's massive search and recovery effort to locate and retrieve a lost atomic bomb off the coast of Palomares, Spain in 1966, from 2,850 feet (869 meters) of water. Working beyond its maximum depth, and actually becoming entangled in the parachute shroud lines attached to the bomb, it managed to recover the weapon and gain instant fame, as shown in the figures on the following page.

CURV's military parents were proud, and rewarded the child with an expanding family. The funds began to slowly flow to support additional work within the Navy laboratory and the technology began to be developed. Smaller vehicles were investigated for shallow water: *SNOOPY* (see figure on next page), which was hydraulically operated from the surface, followed by *Electric SNOOPY*. And, along with the other vehicles, the *CURV*'s ability continued to be advanced, and more units were built.



***CURV* Recovers H-bomb off Palomares Spain**

US Navy's Hydraulic *Snoopy*



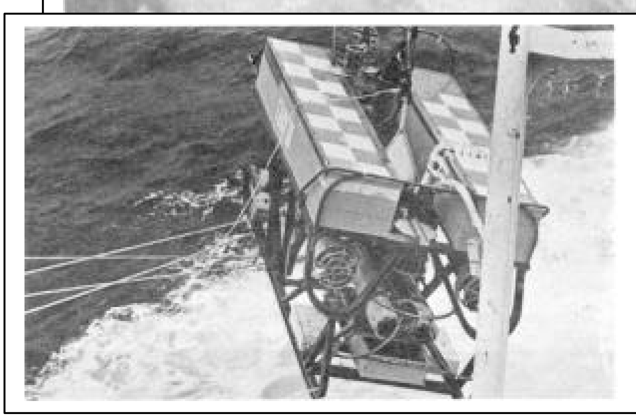
Hydro Product's *Tortuga*

On the commercial side in the US, Hydro Products was getting a jump on the field with their Navy funded programs: *TORTUGA* (see figure, previous page) and *ANTHRO*. The *TORTUGA* vehicles were developed to investigate deployment from a submarine, and the systems ranged from small water jet controlled vehicles to units using propellers for increased maneuvering. The *TORTUGA* was followed by the *ANTHRO*, which investigated anthropomorphic controls, using "head coupled" video and audio feedback to a unit mounted on the operator's head. In addition, they were developing a small, submersible launched vehicle called the Advanced Maneuverable Underwater Viewing System (*AMUVS*) for the US Navy. Hydro Products would soon use this base to start their RCV line of systems.

Unfortunately for the development of ROVs, they still took second billing to the manned submersibles, which offered the *in situ* operator the ability to perform work at a remote site. Saturation diving and manned submersibles flourished as ROV development continued slowly, and by 1974, just over 20 vehicles had been constructed. To this point, government funding was the key, and 17 of the vehicles were totally funded by various governments (US, France, England, Finland, Norway and USSR) to conduct military tasks or perform scientific research.

France was in the technology run with their Navy developments including the *ERIC* and *Telenaute*. ECA had their *PAP* minecountermeasure vehicles. Finland had the *PHOCAS* and Norway the *SNURRE*. The UK was pulling the British Aircraft Corporation (BAC) from the sky to the underwater world with the development of the *BAC-1*, soon to be the *CONSUB 01*; the Admiralty Weapons Research Establishment teamed with the Admiralty Underwater Weapons Establishment (AUWE) to produce the *SUB-2*; and then AUWE continued with their *CUTLET*, *CURV I* style, vehicle for torpedo recovery. The Soviet Union was not to be left out, and the Institute of Oceanology, Moscow, produced the *CRAB-4000* and *MANTA* vehicles. The only real academic presence in tethered ROVs at that time was at the Heriot-Watt University, Edinburgh, where the *ANGUS* line of vehicles (001, 002 and 003) was being developed.

But there were no real "events" for the new type of vehicles to wrestle the limelight away from divers and manned submersibles, and slowly, the growth and capability of ROVs trudged onward until the *CURV III* system once again took center stage. In 1973, the Navy's *CURV III*, which had become a "flyaway" system, was sent on an emergency recovery mission from San Diego to a point offshore, near Cork, Ireland. Trapped on the bottom in 1575 feet (480 meters) of water, the *PISCES III* manned submersible sat with its two occupants slowly reaching the end of their air supply. The final recovery line was attached to the vehicle with a "Rube Goldberg" toggle bolt made on-site using a crescent wrench, two pieces of steel channel and some bungie cord. It worked, and the recovery was successful as the two men emerged with, according to pilot Roger Chapman, only seconds of air remaining. The spotlights hit the ROV, front-page headlines were achieved, and the child's voice began to crack–adolescence had begun.



CURV III* rescue of *PISCES

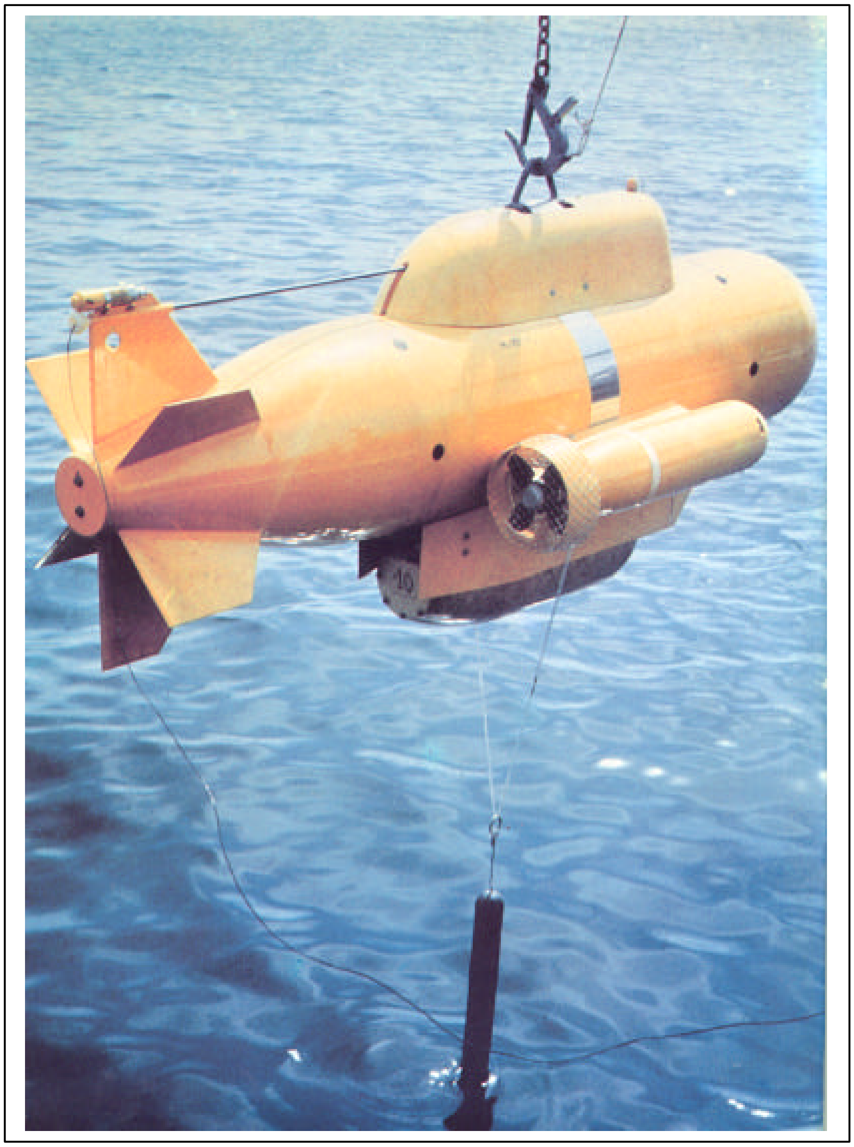
Adolescence (1975-1982)

Adolescence is generally tied to a growth spurt, accented by bouts of unexplained or irrational behavior. Although the span of this period for ROVs is debatable, and many may say it is still continuing, it does however provide a milestone point. The development curve turned upward in a nearly exponential fashion and by the end of 1982 over 500 vehicles had been developed.

Another important change taking place was the funding source. Whereas 85 percent of the vehicles built from 1953-1974 were government funded and operated, 96 percent of the 350 vehicles produced in the next eight years (not counting the *PAP 104*s discussed below) were funded, constructed and/or bought by private industry.

Not included in the above statistics is the production of a specialized ROV called *PAP-104*. The *PAP-104*s, manufactured by Societie Eca, Meudon, France, were flowing off a high-speed production line–relatively speaking. The small mine neutralization vehicle, which could inspect and identify explosive ordnance with its onboard CCTV, had the capability of delivering an explosive charge to the site, which would then be detonated from the surface. It was simple in design, carried on-board batteries for power, and hugged the bottom using a drag weight. It was also relatively inexpensive and, thus, became very popular. By the end of 1982, over 200 of the vehicles had been constructed and delivered to various navies throughout the world.

But the times were changing, and the military dominated industry was taking on a new look. The challenge of retrieving offshore oil and gas efficiently, especially in the North Sea, was becoming a driving factor in the growth of the ROV industry. The advancements in the technology necessary to reduce the larger sizes of the vehicles continued. Foremost was the advancement of the electronics industry, which aided in the miniaturization of the onboard systems, and their associated increase in reliability.



ECA's *PAP-104*

Such miniaturization was exemplified by Hydro Products' "flying eyeball"–the *RCV 125*, which hit the currents in 1975, a spin-off of their earlier *TORTUGA*, *ANTHRO* and *AMUVS* technology. This was soon followed by the *RCV 225*, and eventually the *RCV 150* (shown on the following page). Although the flying eyeballs entered the oil patch gently, usually as a safety tool for divers, and were often seen bobbing off in the distance without their tether, they were there none the less, and were being accepted–slowly.

Drew Michel taking delivery of RCV 225s, serial numbers 6, 8 and 9, from Chuck Strickland

One of the pioneers of the ROV industry was Drew Michel (see above photo), who recognized that these still immature vehicles had a place offshore. While working with Taylor Diving in the Gulf of Mexico, he demonstrated the potential of the small vehicles and led their introduction into the oil industry. Although there was the periodic failure, their successes overcame any reliability problems and they soon began the road to acceptance. It did not take long, and Michel was filling the more international role of unofficial "ambassador" between the US oil fields and the UK. The vehicles were beginning an international role and the US developers were smiling.

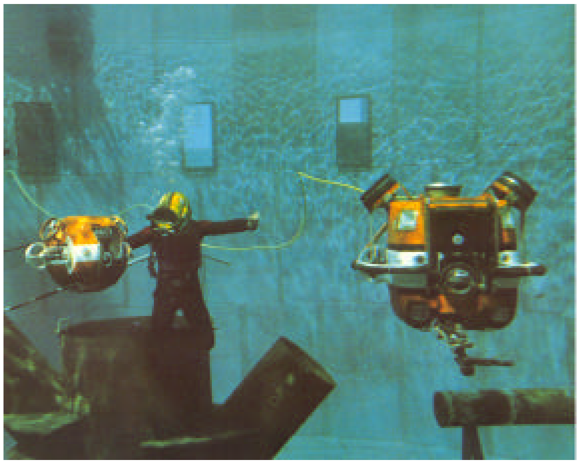
But Hydro Products wasn't the only manufacturer. AMETEK, Straza Division, also in San Diego, developed the *Deep Drone* for the US Navy and soon turned that into their *SCORPIO* line of vehicles. Perry Offshore in Florida picked up the US Navy's design of the *NAVFAC SNOOPY* vehicle and soon had a line of vehicles called *RECON* on the market. Figures are shown on the next page.

Taylor Diving's RCV 225 (above)

With the ability to procure standard ROVs from the now oil-dominated industry, or contract for their services, the US Navy turned it eyes to deeper ventures, chasing the magical 20,000-foot barrier. In addition, the success of the *CURV III* provided the impetus for the Navy to begin the development of the Mine Neutralization Vehicle (*MNV*), an ROV designed to meet stringent military specifications. The *MNV*'s mission was to attach cable cutters to a mine or drop a small bomblet nearby, to be detonated later with an acoustic signal after the vehicle was safely recovered.

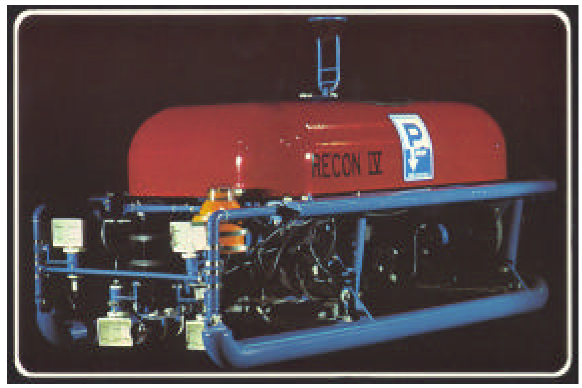
Worldwide, vehicles were being produced, and many new players began to emerge. International Submarine Engineering (ISE) started in Canada (*DART*, *TREC*, and *TROV*). In France, Comex Industries added the *TOM-300*, C.G, Doris produced the *OBSERVER* and *DL-1*. Italy's Gay Underwater Instruments unveiled their spherical *FILIPPO*. The Netherlands were in the picture with Skadoc Submersible Systems' *SMIT SUB* and *SOP*. Norway added Myers Verksted's *SPIDER*, and Sweden added SUTEC's *SEA OWL* and Saab-Scandia's *SAAB-SUB*.

The UK continued to be a world leader with Design Diving Systems' *SEA-VEYOR*, Sub Sea Offshore's *MMIM*, Underwater Maintenance Co.'s *SCAN*, Underwater and Marine Equipment Ltd.'s *SEA SPY*, *AMPHORA*, and *SEA PUP*, Sub Sea Surveys Ltd.'s *IZE* and Winn Technology Ltd.'s *UFO-300*. But, all is not fun and games as several vehicles disappeared from the market–*CONSUB 1* and *201*, *BOCTOPUS*, *SMARTIE*, and *CETUS*. RIP!



***RCV 225* and *150* with diver**

Perry *RECON IV*



SCORPIO

Deep Drone

Japan was entering the picture and soon Mitsui Ocean Development and Engineering Co., Ltd., had the *MURS-100*, *MURS-300* and *ROV*. Germany was also continuing with the addition of Preussag Meerestechnik's *FUGE*, and VFW-Fokker GmbH's *PINGUIN B3* and *B6*.

The big three in the US continued to expand their line of vehicles and Kraft Tank Co. (*EV-1*), Rebikoff Underwater Products (*SEA INSPECTOR*), Remote Ocean Systems (*TELESUB-1000*), Exxon Production Research Co. (*TMV*), and Harbor Branch Foundation (*CORD*) also joined the party.

The growth spurt had been dramatic, and ROVs began to mature to the point where they were accepted at the dinner table with the other adults–manned submersibles–and their subsequent growth and dexterity in the field eventually dwarfed that of their proud, if slightly overweight, predecessors.

"Immaturity" (1982-1989)

Why "immaturity" you ask? Well, even though one goes through adolescence, there still continues a series of regressive states where a return to the irrational, unreliable behavior–if not the fetal position–is experienced. Technology is being advanced. System upgrades are being made. Deeper depths are being assaulted. The competition is cutthroat. And as always, "stuff" happens." The systems are doing more, for less cost and growing rapidly in number. The offshore industry is experiencing a growth spurt in the early eighties and the first conference dedicated to ROVs is held in San Diego in 1983. Ignoring–or possibly using–the confusion associated with rapid industrial growth, the theme of the ROV '83 conference rang a rally bell heard 'round the world–it truly was "A Technology Whose Time Has Come!"

And come it had. In 1970 there was only one industrial manufacturer of ROVs, by 1984 there were 27, but the North American firms (Hydro Products, AMETEK (Straza Division) and Perry Offshore in the US, and ISE in Canada) cornered the market, accounting for 229 of the 340 industrial vehicles produced since 1975. The new kid on the North American block, however, was ISE. Canadian entrepreneur (Jim McFarlane) bought into the business with a series of low cost vehicles–*DART*, *TREC* and *TROV*–and International Submarine Engineering in Vancouver, British Columbia became a competitor. Not initially known for their reliability, they never the less made a foothold and provided whatever the user wanted, becoming a world leader in the production of reliable industrial grade ROVs.

So, with such a strong North American technology base, what happened to its dominance of the market in the early days of maturity? To put it simply, a driving factor was the dollar versus the pound. The US Navy quit developing their own vehicles to use on their test ranges because they could get them cheaper from industry. In the same manner, the ROV technology base established in the US was transferred to the North Sea arena to support the vehicles that were being developed in the US and then shipped there to support the oil patch. By the mid eighties, the dollar and the pound had neared parity, and it became more cost effective for the US manufacturers to produce the vehicles in the United Kingdom than to produce them in the US and ship them overseas. It also was a matter of survival, with companies such as Slingsby Engineering, Sub Sea Offshore, and the OSEL Group beginning to corner the North Sea market. It did not take long, and the once dominant North American ROV industry was decimated. The only survivors were ISE, due to their diverse line of systems and the can-do attitude of their owner, and Perry, which teamed with their European competitors and essentially established a foothold in the North Sea.

Even with all the progress in ROV development and acceptance, this was still considered a long period of "immaturity" by many. The offshore market was vicious, and the weak were quickly devoured. The ROVs were trying to kick the divers out of the water, but they were not succeeding. Saturation divers held their seabed and the number of ROV operators began to take a downturn. Part of the problem was attributed to the diving contractors, who were deeply entrenched, with high profits for their long, tedious jobs. The new upstart ROVs, that in many cases could do the job quicker, and cheaper, could have been a big problem if not controlled by the dive companies, which was the case in most instances. Market forces were driving profit margins down and this was subsequently forced on the ROV companies. With the collapse of oil prices in 1986, it became even more brutal. When fighting for financial survival, the last place that critical funds were going to be placed was into R&D.

But, there was survival, and as the number of manufacturers of large ROV systems began to shrink, the developers of the LCROVs began to emerge. The technological advances had finally been made to miniaturize the vehicles to a point where they were "easily" portable and available at a cost that academic institutions and civil organizations could afford. The first to break through was the *MiniRover*, developed by Chris Nicholson, soon followed by Deep Ocean Engineering's *Phantom* vehicles. Other variations began to appear around the world, however, DOE, and Benthos (which picked up the *MiniRover* line), together cornered the lion's share of the market. New markets were opened in areas including civil engineering, dam and tunnel inspection, police and security operations, fisheries, oceanography, nuclear plant inspection and many others (see section on Inland Operations). The troublesome child was beginning to make a name for himself; one that was not all that bad.

Maturity (1990+)

By the time the decade of the nineties arrived, the ROV industry, at the age of 37, had reached maturity (remember–one ROV year is equal to only one-half of a human year). It had leaped from the eighties, a testosterone filled body of energy ready to get the job done. No work was too hard, too long, or too deep to be completed. The US Navy reached the magic 20,000-foot (6,096-meter) barrier in 1990–twice. The first time was with the *CURV III* vehicle that once again morphed into a deeper, 20,000-foot (6,096-meter) plus configuration. Operated by Eastport International for the US Navy's Supervisor of Salvage, *CURV III* reached a depth of 20,105 feet (6,128 meter). Less than a week later, that record was broken by the Advanced Tethered Vehicle's record dive to 20,600 feet (6,279 meters). The *ATV*, developed by the Space and Naval Warfare Systems Center, San Diego (SSC SD–a.k.a. NOSC, then NRaD), was then transferred to the Submarine Development Squadron Five (formerly the Submarine Development Group) Unmanned Vehicle Detachment in San Diego where it is now operated by fleet personnel. Once again, the Navy had developed the technology, both within their R&D centers and through cooperation with industry, and had closed the door on another era in ROV development.

Enter Japan. What once had been a country with small ROVs that looked similar to US manufactured systems, and organizations that were pursuing long range plans that were ambitious to say the least, Japan stormed onto center stage with a series of excellent vehicles topped by the *Kaiko*. The *Kaiko* not only took over the record for the deepest dive, but also obliterated it, reaching the deepest point in the Mariana Trench–35,791 feet (10,909 meters). A record that can be tied, but never exceeded.

Europe continued to surge ahead with their sophisticated developments and the North Sea became a powerhouse of European built systems. With the end of the Cold War, and the USSR, Russia began declassifying their vehicle programs and unveiled an exceptional talent in getting the job done...anywhere. Likewise, the US Navy began to unveil their secrets in an effort to increase the capability and protection of their submarine fleet (see Military section).

But, it is a large international industry, so what about all the others? Well, we can sum it up with the following: today, a quick estimate indicates there are over 100 vehicle manufacturers, and over 100 operators using approximately 3000 vehicles of various sizes and capabilities. Who they are, what they are doing, and how well they are doing it is discussed throughout this publication. The rest is just ROV history.

Cutting the Apron Strings

The history of unmanned underwater systems may revolve around ROVs, however, the goal of most developers, and especially the academic institutions, is to get rid of the umbilical–assuming everything else can be kept constant, i.e. endurance, bandwidth, reliability, etc. But it can't, and therein lies the question of when it will be acceptable to "cut the apron strings," eliminating the umbilical and letting the mature vehicle go its own way. When will they reach that level of maturity? Hopefully, this publication will answer that question, but for now, let's look into their past.

Rebikoff once again comes into play with one of the first experimental AUVs called the "*SEA SPOOK*," with its prototype "*Jonah*" tested at a speed of 10 knots (18.5 km/hr) in 1960 in France. The next operational AUVs were the Self-Propelled Underwater Research Vehicles (*SPURVs*), developed by the Applied Physics Laboratory, University of Washington, in Seattle. The torpedo sized AUVs were used by the university to successfully conduct mid-water research. *SPURV 1* began in 1963, followed by the *UARS* in 1972 (the Unmanned Arctic Research Submersible is launched from and operated under the ice pack) and then the *SPURV 2* in 1973.

Others were beginning to investigate the technology in the mid to late seventies. The Shirshov Institute of Oceanology, USSR, developed the *SKAT*, and Japan was delving into the area at the Japan Society of Promotion Marine Industry with *OSR-V*, and a research vehicle at the Japan Marine Science & Technology Center (JAMSTEC).

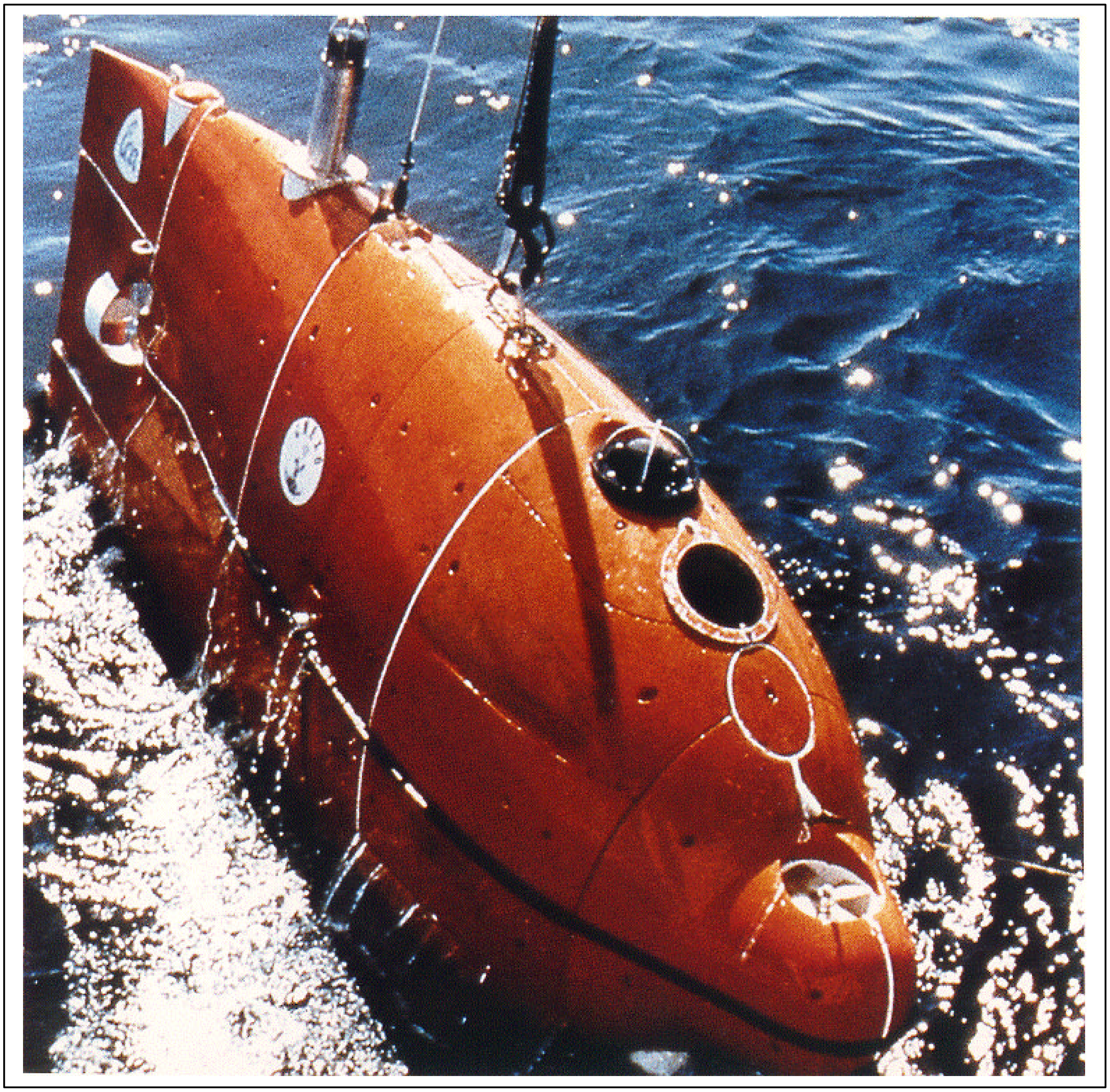
The US Navy continued with the *EAVE West* at SSC San Diego (formerly NOSC), *RUMIC* at the Coastal Systems Station (formerly the Naval Coastal Systems Center) and *UFSS* (Unmanned Free Swimming Submersible) at the Naval Research Laboratory; and, the University of New Hampshire was funded to work on the *EAVE East* (*EAVE III*).

France remained a leader in producing vehicles that achieved results, and continued the tradition with the team of IFREMER and ECA developing the *Epaulard*, which began in 1977 (see figure next page). Although there had been limited progress in the area of AUVs prior to 1980, the eighties has to be considered the decade of the AUVs. *Epaulard* became operational in 1981 and within the next five years had covered over 500 miles (805 kilometers) underwater with a payload capable of exceeding 200,000 photographs. The 19,685 foot (6,000 meter) capable vehicle, although battery operated and following pre-programmed paths, was essentially tied to the bottom, taking a design element from the *PAP-104* vehicle–the bottom drag weight.

By 1984, there were 17 AUVs under development, but only the *Epaulard* and *SPURV* systems could be considered operational. The developmental systems were rather evenly split between commercial, academic and military organizations. The only vehicles, besides those mentioned above, to achieve any notoriety were the *ARCS* by ISE, *AUSS* by SSC San Diego, *EAVE-East* by the University of New Hampshire, and *SKAT* by the Institute of Oceanology in Moscow.

The need for higher capacity energy sources for onboard power, more computing power, lighter instruments with higher efficiency, better navigation, and all the related technologies kept the AUV family from progressing more rapidly. The academic community was picking up speed, yet the impetus for AUV development was still coming from the military side of the house. Speculating on the future, Martin Marietta Aero & Naval Systems developed the Mobile Undersea Systems Test (*MUST*) Laboratory, in cooperation with Applied Remote Technology (ART) in San Diego. The 4.5-foot (1.37-meter) diameter, 30-foot (9.1-meter) long *MUST* vehicle became operational in 1988. It was immediately followed by ART's torpedo sized *XP-21* vehicle, adapting a lot of the software developed under the *MUST* contract.

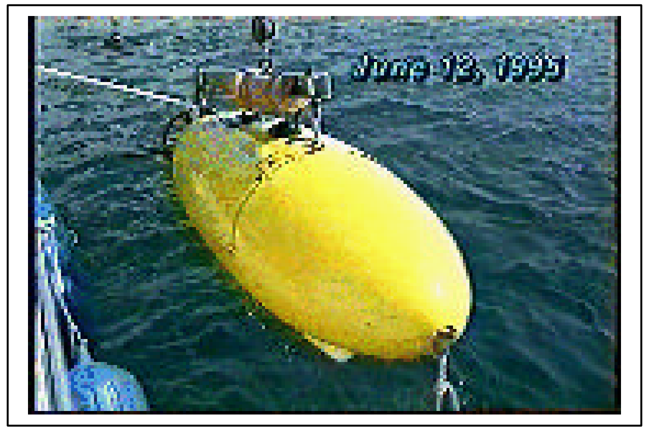
Unfortunately for ART and Martin Marietta, the US military was concurrently planning its own testbed AUVs under the sponsorship of DARPA, resulting in a $24M contract in 1988 with Charles Stark Draper Laboratory, Inc., Boston, MA. The Navy had its test beds and the *MUST* and *XP-21* would go without the financial prize they both sought. (See Test Bed AUVs section later in this chapter for additional information and photos).



The French EPAULARD

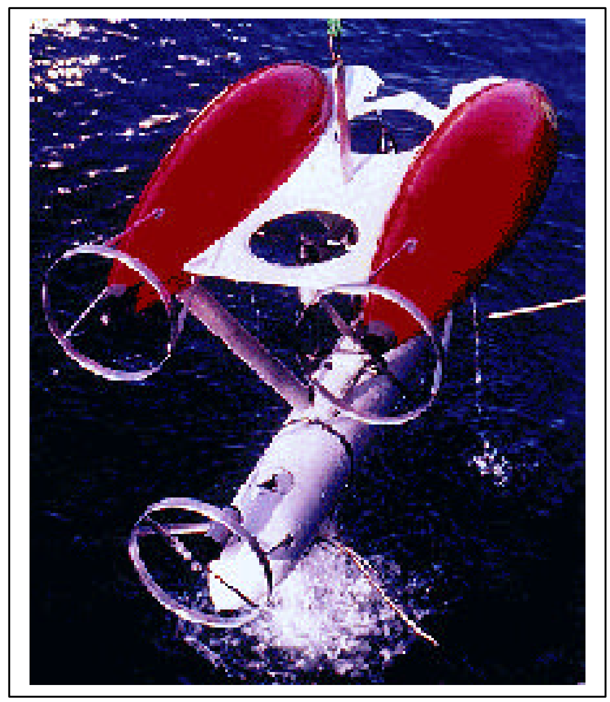
The biggest surprise of the eighties (although not fully unveiled until the early nineties) was the large program ongoing in the USSR. The *MT '88* vehicle (also known *as Sea Lion*) had been developed by the Institute of Marine Technology Problems (IMTP), Vladivostok, Russia. The *MT '88*, along with its predecessor vehicles, although not as sophisticated as some others being developed internationally, had been operational for some time. And they were in the field working. The *MT '88* had been used to survey two sites where former Soviet submarines had sunk, the *Komsomolets* off Norway in 6,500 feet (1,981 meters) of water and the Yankee-class SSBN in the Atlantic in over 18,000 feet (5,486 meters) of water. The more simplistic vehicles were highly reliable and operated with excellent results.

ISE's *DOLPHIN*



OCEAN VOYAGER

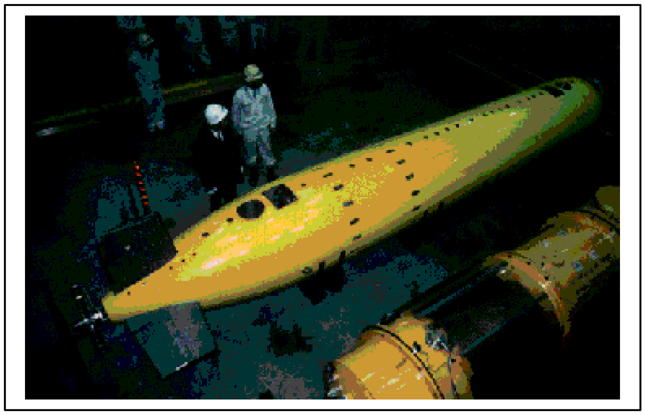
MIT's *ODYSSEY IIB*



WHOI'S *ABE*

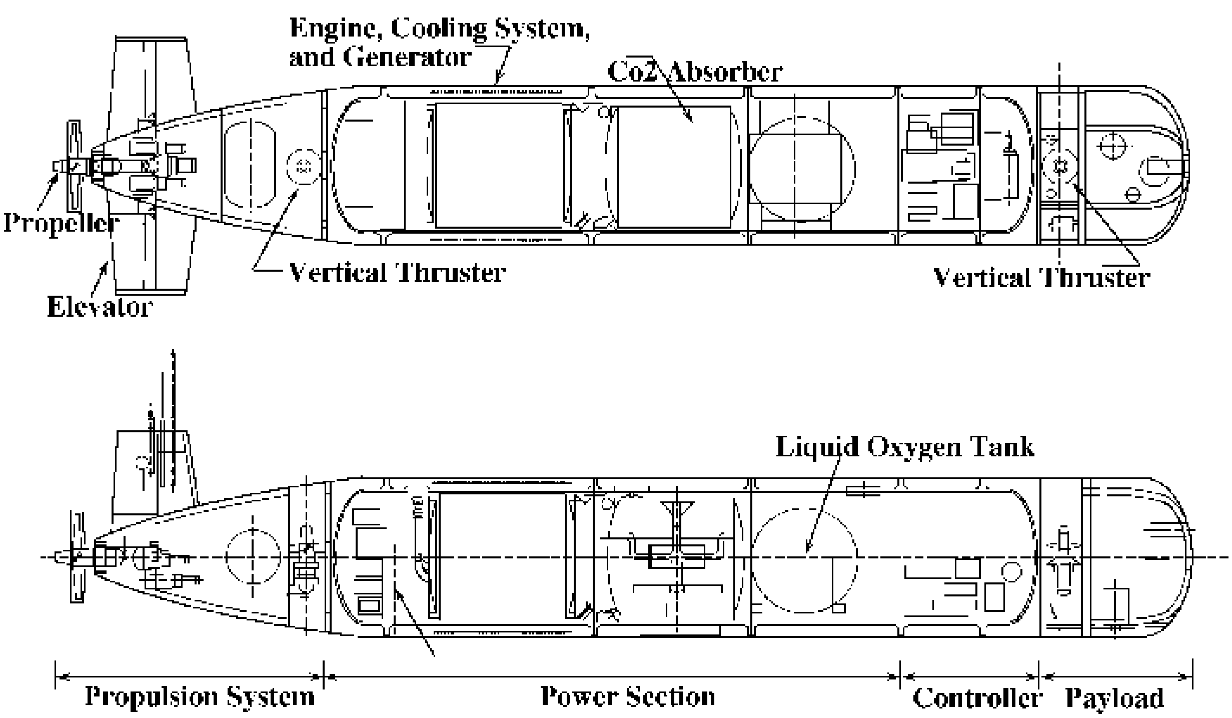
In the decade of the nineties, the pace was picking up; not so much in the military, but more so in the academic community. In the US, Woods Hole has *ABE*, Florida Atlantic University has the *Ocean Explorer* and the *Ocean Voyagers*, and MIT has the *Sea Squirt* and *Odyssey*. In Canada, ISE has added the *Dolphin* and *Theseus* vehicles. The IMTP in Russia is enjoying privatization, developing the *Tunnel Sea Lion* for the US and the *CR-01A* for China–they also unveil their *Typhlonus* vehicle.

Europe is busy. The UK's Institute of Oceanographic Sciences, Deacon Laboratory (IOSDL)–now the Southampton Oceanography Center–was developing the *DOGGIE* and *DOLPHIN* vehicles, which have now merged into the *Autosub*; Marconi has their torpedo sized Research AUV. France's Thompson Sintra is developing the Mini Autonomous Underwater VEhicle (*MAUVE*) as part of the MArine Science and Technology (MAST) program, a European consortium that also includes, Portugal, Italy, Denmark, and Belgium. Denmark adds the *Marius* and *Martin* vehicles, also under the MAST program. Japan moves onward with their *Twin Burger*, *Aqua Explorer*, *Pteroa 150* and the closed cycle, diesel powered *R-One Robot* vehicles.



***Autosub* (above left)**

The University of Tokyo *R-1 Robot* (above right and below)



The assault on the oceans is beginning in earnest–the apron strings are about to be cut. Just how soon they'll be cut, and other discussions regarding the previous and most recent systems and programs, will be presented in more detail throughout this publication.

The Rest of the Family

To wrap up the history of unmanned underwater vehicles, we need to address the "rest of the family." These include bottom crawling/towed vehicles, towed (mid-water) vehicles, and hybrids such as structurally reliant systems, i.e. they need to attach to something other than the bottom to perform their job.

Bottom Crawling/Towed Vehicles

The evolution of vehicles in this category began with the advent of the transatlantic telegraph telephone cables. From the very beginning, fishermen and cables were adversaries. On the evening of 28 August 1850, a submarine cable was laid across the English Channel. By daylight of the following morning a fisherman hauled the cable out of the water and, instead of simply dropping it back in, cut out a piece to show his contemporaries ashore. In spite of international treaties for the protection of underwater cables, fishermen continued, intentionally and unintentionally, to be the main cause of cable failures. The solution, after many false starts, was to bury the cables where they could not be fouled by trawling gear.

One of the early pioneers in cable burial was Mr. C. S. Lawton of the Western Union Telegraph Company. He designed a surface ship towed cable plow in 1938 that was used to bury some 43 nm (79.6 km) of cable to an average depth of seven inches (17.8 centimeters) off the coast of Ireland. Other companies, such as the Nippon Telegraph and Telephone Corporation in Japan, and the Hamsdorf Corporation of Holland, also developed vehicles for cable burial. They relied on jetting principles which, at the time, were either limited to protected waters or to diver depth. Lawton's towed plow seemed to be the best approach to the cable burial problem.

The Bell Telephone Laboratories, beginning in the 1960's, made significant advances in cable burial. After experimenting with a variety of burial techniques, Bell Laboratories finally settled on the plow principles and produced a series of cable burying plows, designated *SEA PLOW I*, *II*, *III* and *IV* during the period 1966 through 1983. The first commercial application was in 1967 with the burial of replacement sections of the submarine cables TAT-3 and TAT-4 off the coast of New Jersey.

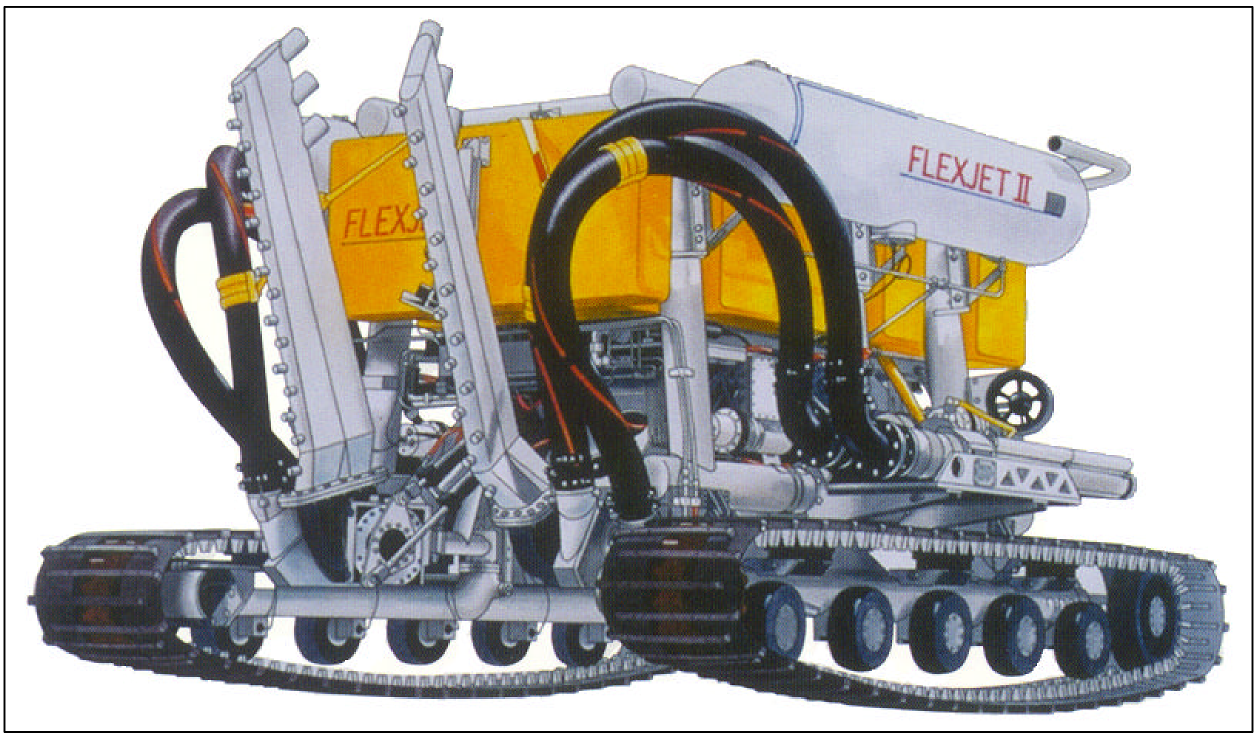
From the early sixties through the early eighties, a wide variety of bottom-crawling vehicles were designed and over 73 were actually built and demonstrated. By far, the major application was for cable and pipe trenching. Through 1975 cable trenching dominated; then, in the mid-seventies, pipe-trenching vehicles began to dominate.

This trend was reflective of the surge in offshore oil and gas activity, particularly in the North Sea. Since then, vehicles with both pipe and cable trenching capabilities have begun to appear, particularly in Europe.

Until the 1970's the US was dominant in building and utilizing bottom crawling vehicles. However, after 1970 other countries became active in this field and, in several instances, equaled or exceeded US production, especially those in the UK.

Today, companies such as AT&T Submarine Systems do not waste a minute in applying bottom crawling vehicles such as the *SCARAB* to bury their expensive cables (see Cable Burial section in Chapter 4). These world wide cable routes are buried do a depth of approximately 3.28 feet (1 meter) out to a water depth of approximately 2,952 feet (900 meters). Loss of these communication cables, which are susceptible to everything from shark bites to seismic activity, can cause the company losses on the order of $1 million an hour.

Using state-of-the-art technology, companies such as Perry Tritech are combining ROVs with cable burial systems to produce vehicles such as the *Flexjet II*. This vehicle combines a *Triton* Work System as the prime mover for the *Flexjet II* (see figure below) providing a highly versatile burial system. The unique aspect is that the *Triton* ROV can be removed from the trencher system and be used as a stand-alone system.



***FLEXJET II* Burial System**

Unlike the tethered, free-swimming ROV's, bottom-crawling vehicles were not built on the speculation that a buyer would be found. These vehicles were generally built by the company that also operated them; or they were built on order to the specifications of the operating company. Also, in no instance are two vehicles identical. Where a series of vehicles was constructed, each succeeding vehicle differed from its predecessor. Another fundamental difference between bottom crawling and tethered, free-swimming ROVs is that the former are almost always designed for a specific task; not for general purpose (the exception being light work/inspection vehicles). Yet, another unique feature of this vehicle class is that they are rarely advertised for use from a ship-of-opportunity. In almost all instances, they require a dedicated ship or are designed to be deployed from a specific ship or platform. Since bottom crawlers and towed plows are usually massive and require extensive surface support and heavy-duty launch/retrieval devices, they are greatly restricted to a platform that can provide adequate handling facilities.

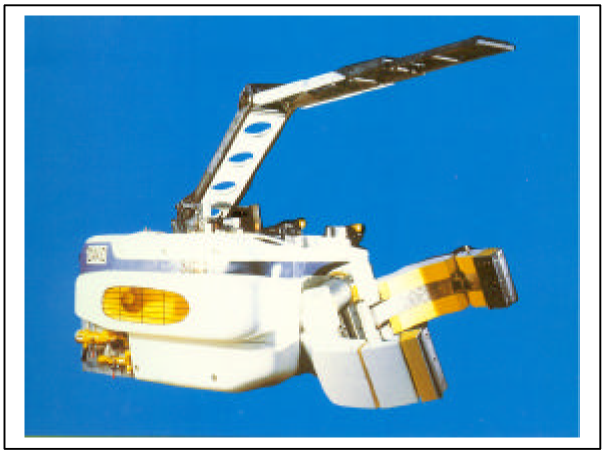
Hybrids

Hybrid vehicles could almost be placed in the other categories depending on how you define them, however, it would be correct in saying that they are neither free-swimming, nor towed along the sea floor. Essentially, they rely on something else to put them in place, and allow them to remain there. Structurally reliant would be a good description, if one assumes that the structure is reached with assistance. Such systems still obtain their power and control from the surface, however, propulsion is obtained from wheels, tracks or push-pull rams in contact with a structure. Some mid-water capability often exists for the transit to/from the structure.

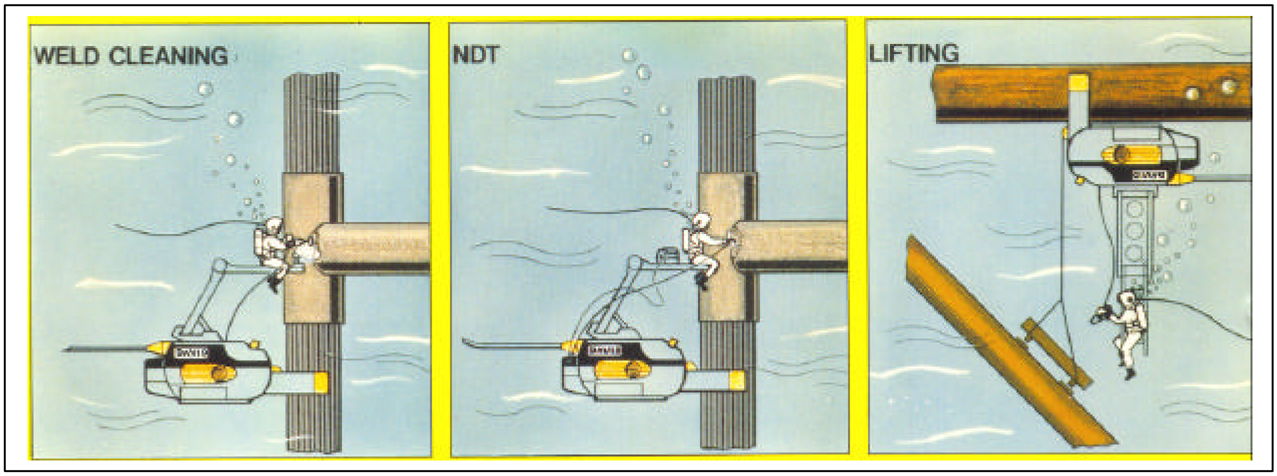
In existence since the early 1970's, structurally reliant vehicles exhibit unique design characteristics for the specialized tasks they perform. Most have TV, and all are designed to perform a single task such as pipeline trenching, oil tank soundings, ship's hull cleaning and inspection, and subsea production system maintenance (SPS) and inspection. One of the simplest tasks of structural reliance would be pipeline inspection, where the vehicle lands on the pipeline, and instead of flying along above it, travels down the pipeline on a wheeled undercarriage attached to the ROV.

Some of the first hull inspection was performed by systems such as Underwater Maintenance Company Ltd.'s *SCAN*. *SCAN* was a wheeled vehicle held against the hull of very large crude oil carriers. Once it flew into position, it would decrease its ballast by filling a tank with air and hold itself against the hull while it performed the survey. Another ROV originally designed exclusively for hull cleaning was the *SCAMP*, developed by Winn Technology Ltd., which was a triple brush system held in place with an impeller while it moved along on wheels.

A good example of a hybrid system is the *DAVID* vehicles developed by HERION Systemtechnik GmbH of Germany (see below). Built originally in 1985, these large ROVs were designed to attach to large underwater structures using a gigantic rotatable claw. Once in place, the diver was assisted in IMR and other work by using the tools that the *DAVID* carried, its onboard hydraulic supply, ladder, crane and other support features. Three were built, followed by a second generation in 1989 called *MARS*, with similar features.

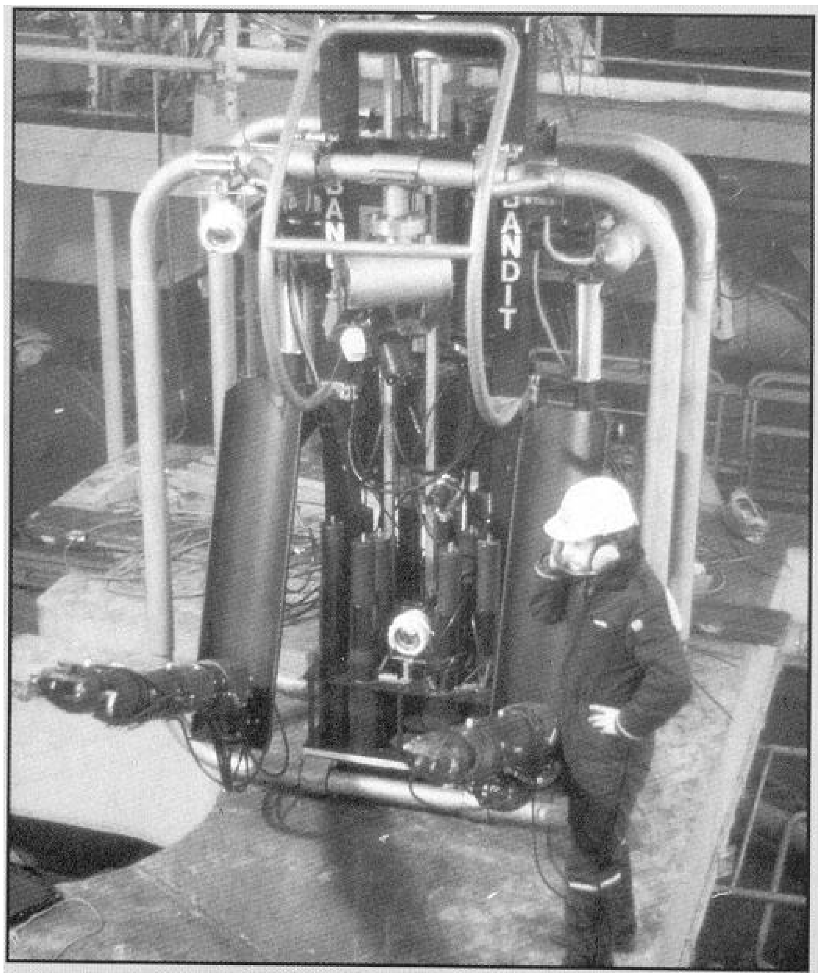


The surrounding photos (clockwise) show *David*, *David* with a Diver, and *David* Operating Concepts



SEATEC B.V., The Netherlands, with the development of the Remote Operated Hovering Platform (*RHOP*) in 1989, addressed working in extreme sea states. The heavy-duty winch cable lowered system was capable of using manipulators and tools to undertake inspection, debris clearance, or salvage operations.

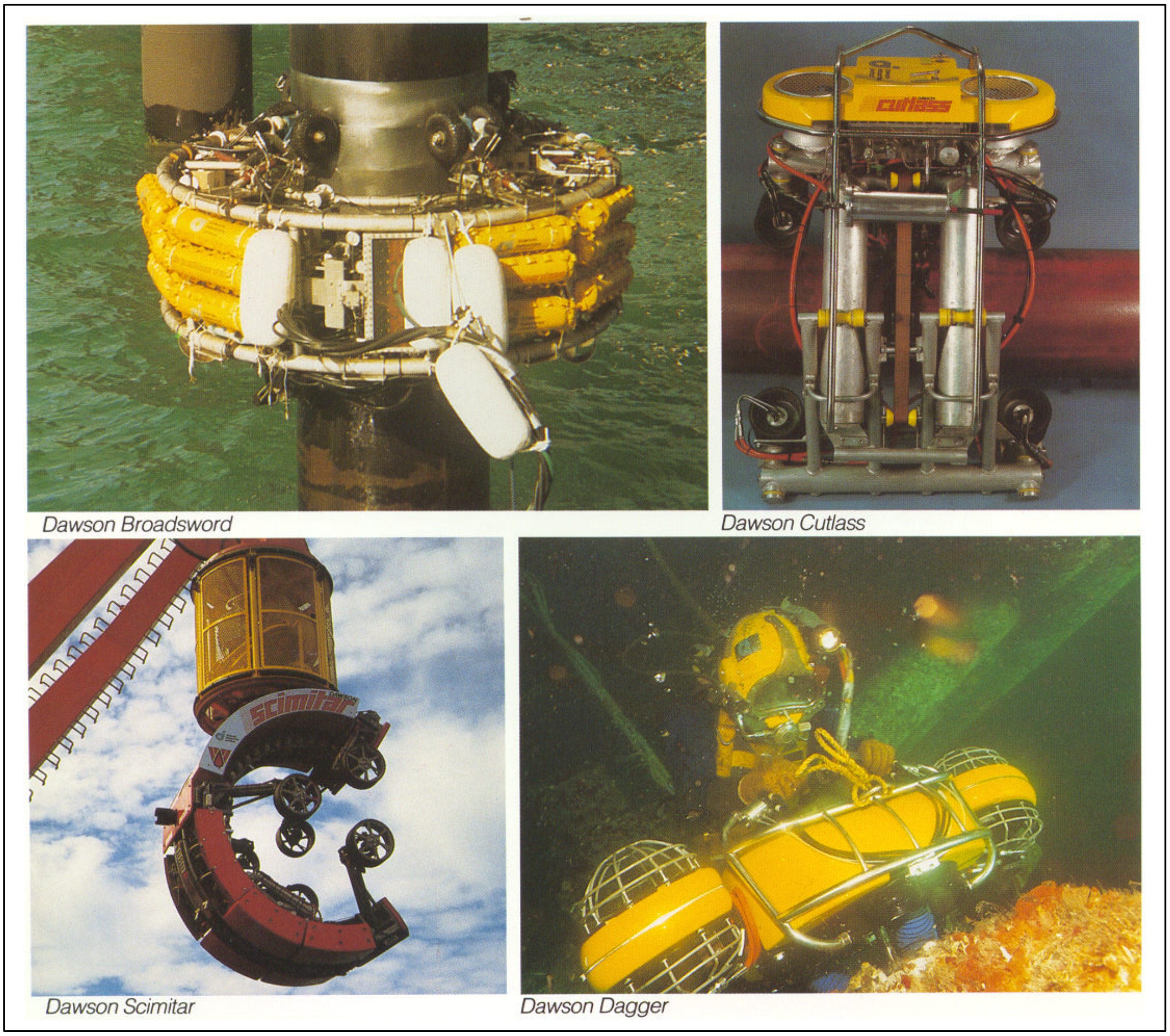
A similar system was Deep Ocean Engineering's *BANDIT*, a manipulator system developed primarily to support drilling operations. Bandit could be lowered down guide wires and securely held in place while it performed maintenance on the blow out preventor and riser.



***BANDIT* Manipulator System**

With the requirement to go into deeper waters, the deployment of Remotely Operated Maintenance Vehicles (ROMVs) is required. Such a system, essentially a remotely operated tool (ROT) that has the ability to move about within the structure, has been incorporated into Saga Petroleum's Snorre Subsea Production System.

When it came to developing hybrid systems to clean offshore structures in the mid-eighties, it was hard to match the unique array of systems developed by Dawson Industries Ltd., of Western Australia. The fact that they felt they were "a cut above the rest" in this portion of the market was reflected in the names of their systems: *Broadsword*, *Cutlass*, *Dagger* and *Scimitar*. These systems, although not really vehicles, were large ROTs that could be integrated with an ROV for emplacement; divers could move the smaller ones into place.



Dawson Broadsword
Dawson Cutlass
Dawson Scimitar
Dawson Dagger

Dawson's Hybrid Systems

And the examples do not end. There is the TLP Riser Inspection Vehicle developed by Tecnomare Industriale S.p.A, Italy, for outside inspection and removal of marine growth from the Snorre TLP risers. They also developed the TLP Tether In-Service Internal Inspection Vehicle for internal ultrasonic inspection of the TLP tether welds. Tecnomare's *TM 253* is a seabed corer and bottom sampling device. Boskalis Offshore BV, The Netherlands, uses the *NAMROD* for underwater excavation and material sampling to locate diamond deposits. Mitsui Engineering & Shipbuilding Co. Ltd., of Japan, built the *RTV-KAM* for internal inspection of power plant conduits with a special array of color cameras.

Whether inspecting or cleaning, internal or external, or running around a subsea production system on tracks while performing maintenance operations under direct or supervisory control, the hybrid systems are there to meet the challenge. The only limitation is one's imagination–and the size of their pocketbook

Towed (Mid-Water) Vehicles

Towed systems are similar in many cases to tethered ROVs, however, in most cases they are very heavy and receive their propulsion power from the surface platform, which tows them through the water. Because of their high strength cables, some of them up to 30,000 feet (9,144 meters) long, that provide the power and telemetry link to the "fish," they were the first vehicles to reach deep water; however, they are limited in what they can achieve. Their forward motion of from 1-8 knots (1.85-14.83 km/hr) is provided by the ship, their vertical movement by the winch operator and lateral movement comes from complex ship maneuvers, or in the case of some of the more recent vehicles, side thrusters that afford a small amount of deviation from the basic ship's track. The fact that they do not have to meet stringent buoyancy requirements lends them to outfitting with wide arrays of cameras, sonars, and other sensor suites.

Just which of the towed vehicles was the first is unclear, however, by 1978 there were only 10 such systems accounted for, and only two of them were owned by private industry, which again highlights the importance of the government in underwriting the technology. The US Navy owned the Scripps Institution of Oceanography, Marine Physical Lab *DEEP TOW*, NAVOCEANO's *TELEPROBE* and Naval Research Laboratory's *MIZAR*. The US National Marine Fisheries Services owned *RUFUS I* and *II* (Remote Underwater Fishery Assessment Systems), and the University of Georgia had *S3* (S cubed) (Seafloor Surveillance System). In Nova Scotia, Canada, the Bedford Institute of Oceanology developed the *BATFISH* and in the USSR, the Institute of Oceanology, Moscow, developed the *CRAB*. The two commercial systems were owned and operated by Hydro Products, with their internationally sold *DSS-125*, and Alcoa Marine Corp., with their *SEA PROBE*, which was actually deployed by a drill string. Of these systems, the *DEEP TOW*, *DSS-125*, *MIZAR* and *SEA PROBE* could operate to a depth of 20,000 feet (6,096 meters).

Some additional systems, which seem to have been neglected in early documentation, include the *SHRIMP*, developed by Reynolds International Inc., a towed search system deployed from the *M/V Privateer* to depths of 2,000 feet (610 meters); the prototype was completed in 1971. Also, two towed systems operated by the Association of Marine Services, Seattle, WA, the *NEDAR I* and *II*, had operational depths of 10,000 and 25,000 feet (3,048 and 7,620 meters) respectively.

To be totally fair in addressing the historical perspective of towed search systems, those that are not towed mid-water should not be ignored. France had developed three versions of the *Troika* by 1973, a towed camera sled that is drug along the bottom and takes photos at predetermined intervals. It was used successfully in 1969 to locate a Caravelle lost in the Mediterranean Sea.

Germany also had a similar system, produced by IBAK Helmut Hunger, the Deepsea Photo and TV Towing System, that used a drag weight to allow the sled to fly above the sea floor, affording the camera system a better field of view. It was developed to search for manganese nodule deposits in the Pacific Ocean, and was also a 20,000-foot (6,096-meter) system.

The field expanded quickly, and by 1979, other US players included the Woods Hole Oceanographic Institute with *ANGUS*, the Jet Propulsion Laboratory with their 20,000 foot (6,096 meter) capable *DIGITOW*, and Hydro Products, which added their fourth *DSS-125*. West Germany gained two systems; Dornier System GmbH added the 19,685-foot (6,000-meter) *GUSTAV* and *SEP* systems, but GFK Karlsruhe lost their 21,325-foot (6,500-meter) *MANKA 01* at sea. And, France was again a player with CNEXO's 19,685-foot (6,000-meter) *RAIE I* and *II* manganese nodule survey systems.

Deepwater Towed Abyssal System
Deployed from Soviet *R/V Gelendzhik*

By 1981, the Institute of Oceanology, USSR, added their *SOUND* vehicles, capable of 13,123 feet (4,000 meters). The US Navy was developing a 19,685 foot (6,000 meter) capable Surface Towed Search System (*STSS*) under a contract with Westinghouse Ocean Research Laboratory. And, the Towed Unmanned System (*TUMS*) was under development for the Royal British Navy by Sperry Systems and Perry Offshore for operations from the *HMS CHALLENGER.*

Since then, there have been more vehicles built, especially in the area of the lower cost, smaller tow fish, which can deploy a side scan sonar from a small boat, giving the operator an excellent underwater search capability. But, we'll discuss these later in this publication. And, as for the deep towed systems, many more have come on line. Many of today's towed systems, with a capability of 10,000 feet (3,048 meters) or greater, are shown in the table on the following page.

To conclude this brief history, it is apparent that the rate of development of towed systems has slowed–at least when compared to the work type vehicles–but their application remains the same. The interesting aspect of these systems is that the majority of the larger systems can reach 20,000 feet (6,096 meters). This capability underscores the early interest of the commercial and academic community to survey and exploit the seafloor, especially for manganese nodule fields, and the military's interest in prosecuting targets, with the desire to find and retrieve objects from almost anywhere in the ocean.

How well have Unmanned Underwater Systems achieved their goals? What are the true capabilities of such systems, and what will they be doing in the future? Read on, the answers follow.

CURRENT TOWED VEHICLES WITH GREATER THAN 10,000-FOOT CAPABILITY

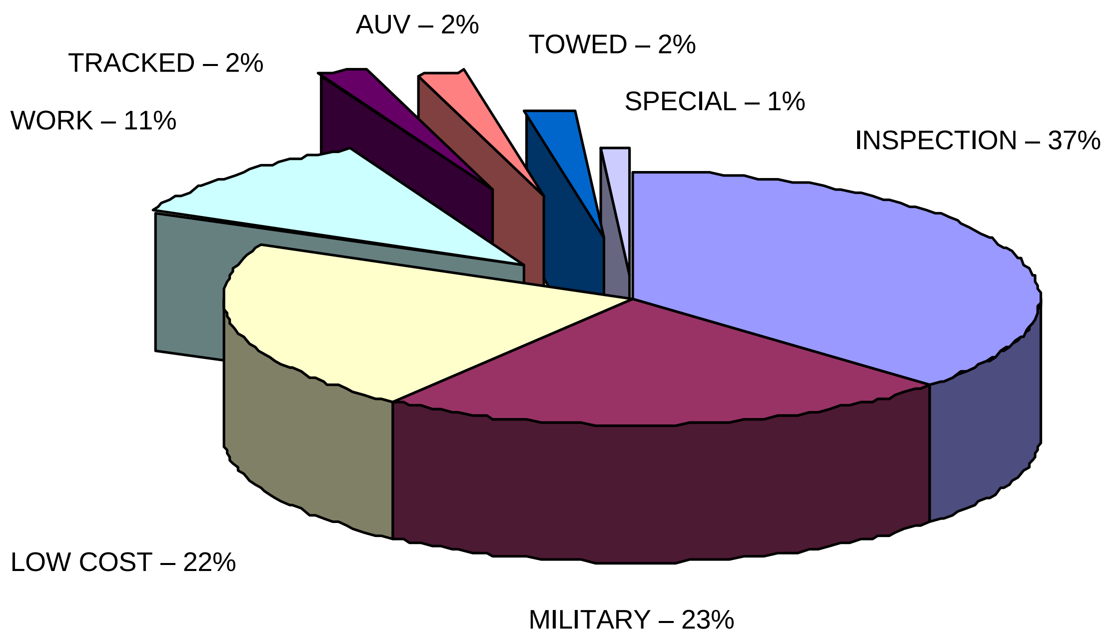
VEHICLE	DESIGN DEPTH	DEVELOPER/OPERATOR
SIS-3000	32,810 FT*	DATASONICS, U.S.
OKEAN	26,248 FT	NIPIOKEANBGEOFIZIKA INST., RUSSIA
DEEP OCEAN SEARCH SYSTEM	26,000 FT	OCEANEERING TECHNOLOGIES INC., U.S.
OCEAN EXPLORER 6000	25,000 FT	OCEANEERING TECHNOLOGIES INC., U.S.
DEEP TOW (FISH 4, 5, & 6)	23,000 FT	SCRIPPS, MARINE PHYSICAL LAB., U.S.
DEEP TOW	21,325 FT	JAMSTEC, JAPAN
ORION	20,000 FT	OCEANEERING TECHNOLOGIES INC., U.S.
TOSS #1 & #2	20,000 FT	WOODS HOLE OCEANOGRAPHIC INST. (WHOI) FOR STENNIS SPACE CTR., U.S.
ARGO II	20,000 FT	WHOI, U.S.
DSL-120	20,000 FT	ACOUSTIC MARINE SYSTEMS & WHOI, U.S.
FISH 103	20,000 FT	INTERSHELF, RUSSIA
ORANI	20,000 FT	KRYLOV INST., RUSSIA
SAR	20,000 FT	THOMSON/IFREMER, FRANCE
TOBI	20,000 FT	SOUTHAMPTON OCEANOGRAPHY CTR., U.K.
MAK-1M (5 SYSTEMS)	20,000 FT	NIPIOKEANBGEOFIZIKA RESEARCH INST., RU OPERATORS: CGGE INTERNATIONAL AND ROMANIAN CTR OF MARINE GEOPHYSICS
URAN-1	20,000 FT	KRYLOV INST., RUSSIA
NPA-6000	20,000 FT	ST. PETERSBURG MARINE ENG. BUREAU, RU
RELIEF 6000-100 RELIEF 4000	20,000 FT 13,120 FT	CENTER OF OCEAN ENG. LTD, BULGARIA
DEEPSCAN 60	20,000 FT	ULTRA ELECTRONICS LTD., U.K.
MSSS	20,000 FT	INTERNATIONAL SUBMARINE TECHNOLOGIES, LAMONT DOHERTY EARTH OBSERVATORY
DEEP TOWED SEAFLOOR MAPPER (SIS-7000)	20,000 FT	DATASONICS FOR U.S. GEOLOGICAL SURVEY
SEAMARC		INTERNATIONAL SUBMARINE TECHNOLOGIES/ WILLIAMSON & ASSOCIATES, U.S.
AMS-120 & 60		ACOUSTIC MARINE SYSTEMS/WILLIAMSON & ASSOCIATES, U.S.
AMS-60		SIMRAD/CHINA OCEAN MINERAL RESOURCES R&D ASSOCIATION, CHINA.

*DEPTH WITH LARGE DIAMETER CABLE

TODAY'S CLASSES OF SYSTEMS

Today's vehicles are manufactured by over 100 companies, operated by over 100 companies and represent nearly 300 different models from ROVs to AUVs and towed to hybrid systems of all shapes and forms. The distribution of different vehicles in this vast array of systems is presented in the following figure and will be discussed throughout this section.

VEHICLE PERCENTAGE BY CATEGORY



SOURCE: *FACING THE DEEPWATER CHALLENGE* BY DAVE LIDDLE
INTERNATIONAL OCEAN SYSTEMS DESIGN, NOV/DEC 1997

Tethered Remotely Operated Vehicles

As discussed in the previous section, most early ROVs were developed for military applications either within the government laboratory system, through government contracts with industry, or a combination of the two. This ultimately resulted in the technology base necessary for commercial applications.

The first commercial ROV system, a Hydro Products *RCV 225*, was delivered to Stolt-Nielsen Seaway Diving in 1974 for use in the North Sea. By the 1983 peak there had been approximately 450 ROV systems built and sold worldwide (see figure on following page). This number continued to rise exponentially and increased to nearly 900 by 1986. Of these, an estimated 575 were used commercially and 325 were used for military purposes.

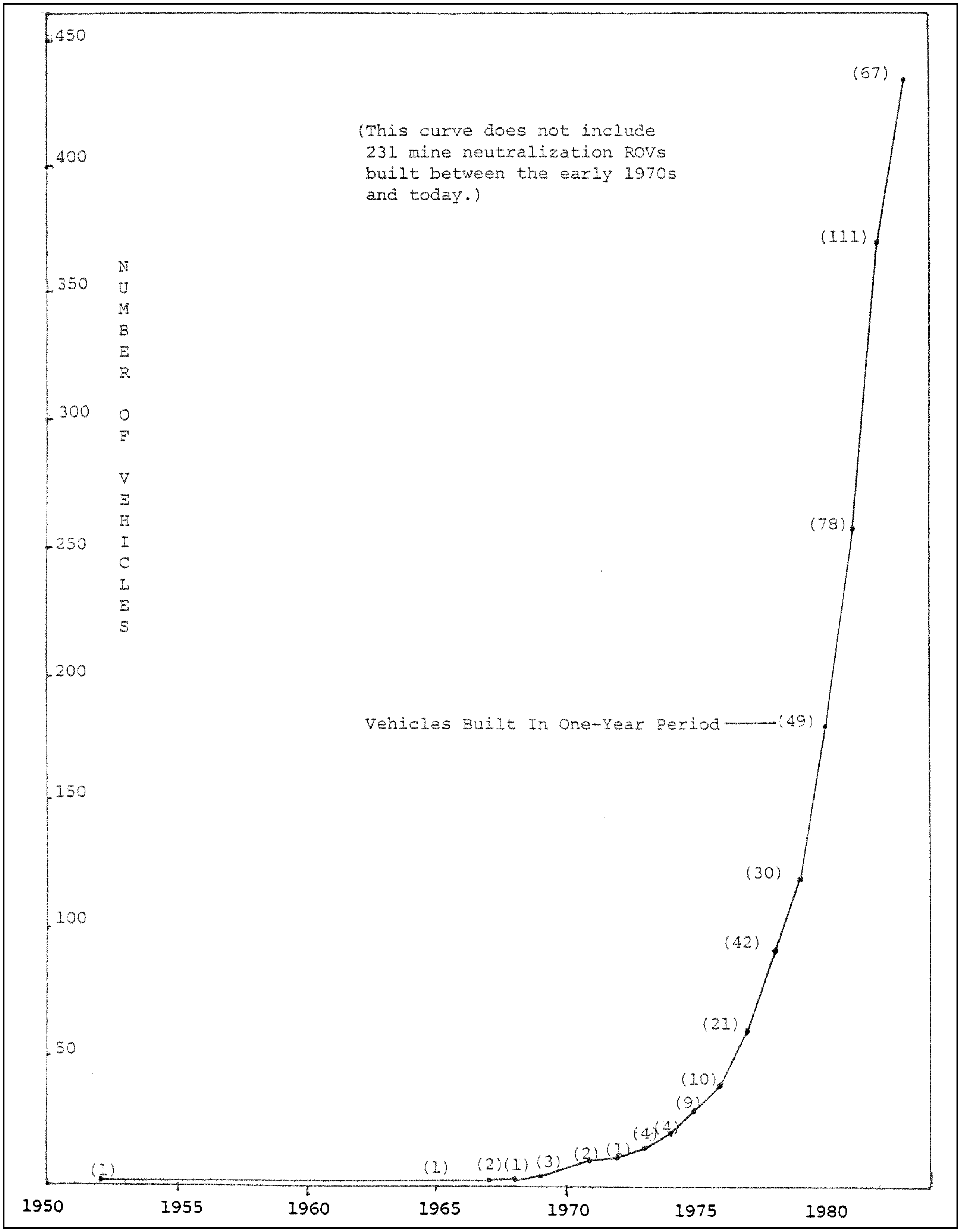
ROVs that operate in today's offshore environment bear little resemblance to those that first began supporting subsea work 15-20 years ago. In that short span of time, an explosion of subsea technology has occurred, rendering older ROV equipment obsolete as subsea remote intervention tasks expanded beyond those originally envisioned.

Modern ROVs employ the latest technology in robotics, fiber optics, acoustics, video and computer technologies, and routinely exceed 90 percent operational availability. Leading ROV operators have demonstrated less than one percent down time over thousands of hours of operation with work class ROVs such as Perry Tritech's *Triton.*™

The current subsea technology trend is to provide complete installation, support and maintenance of subsea projects by ROV deployed tools. With advanced intervention tasks requiring more complex, reliable and powerful tool systems, the requirements of subsea intervention are changing. Present deep subsea work tasks require:

- Powerful ROV systems with flexible control and hydraulic systems
- High reliability - high quality components
- Enhanced vision systems, cameras and laser imaging
- More dexterous manipulators and manipulator control systems
- More up-front planning and design efforts for project tasks

One significant worldwide trend in the oil and gas industry over the past few years has been the move, due to greater water depths, from fixed production platforms to subsea completion systems, tension leg platforms and floating production systems. Concurrent with this trend is an increase in the use of inter-field pipeline systems, resulting in a radical expansion of subsea intervention tasks, which boosts the use of totally diverless intervention.



Tethered ROV Growth Curve – 1952 to 1983

The challenge of operating in deeper water is shaping the technologies needed for ROV intervention today. New technologies are being introduced or crossbred from high tech industries to provide more capabilities in the underwater market. New tools for subsea work will be required, such as pipe repair tooling, automated inspection systems and workover, maintenance and intervention tools.

ROVs can now deploy heavy work packages that perform reliably with high performance results. In deepwater operations, i.e. greater than 9,843 feet (3,000 meters), ROVs will be the only method to support and repair these installations. The ROV market is very strong-based on trends toward subsea completions, remote (diverless) intervention, and deeper water for both oil/gas and telecommunication support. The types of systems of the future are project oriented ROV systems developed in conjunction with major advancements in deepwater. The trend is for ROV suppliers and contractors to now be involved at the earliest stage of project development with hardware suppliers, engineering contractors and the end user.

ROV suppliers now provide a modular base vehicle design with the ability to interface to a variety of tooling configurations with relatively minor reconfiguration. The key requirement is having control, hydraulic and structural capacity to accommodate a variety of missions and tools. Designs must take into account operational requirements based on market feedback as well as operating costs and regional safety and certification requirements such as DNV, NVE, AODC and ABS structural guidelines. The following sections will divide the vehicles into classes and discuss their specific attributes.

Small Vehicles

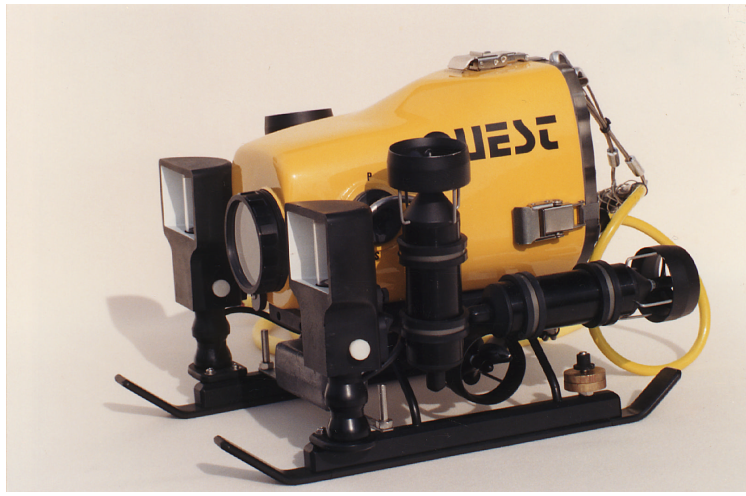
The small vehicle class of ROV includes the majority of "low-cost" vehicles, most of which are typically all electric and operate above 984 feet (300 meters) water depth. These vehicles are used primarily for inspection and observation tasks.

There has been a recent surge in the development of small vehicles, due primarily to the improvement in technology for electrically powered systems. These improvements have resulted in an increase of capability, performance and depth not previously achieved.

Low Cost ROVs

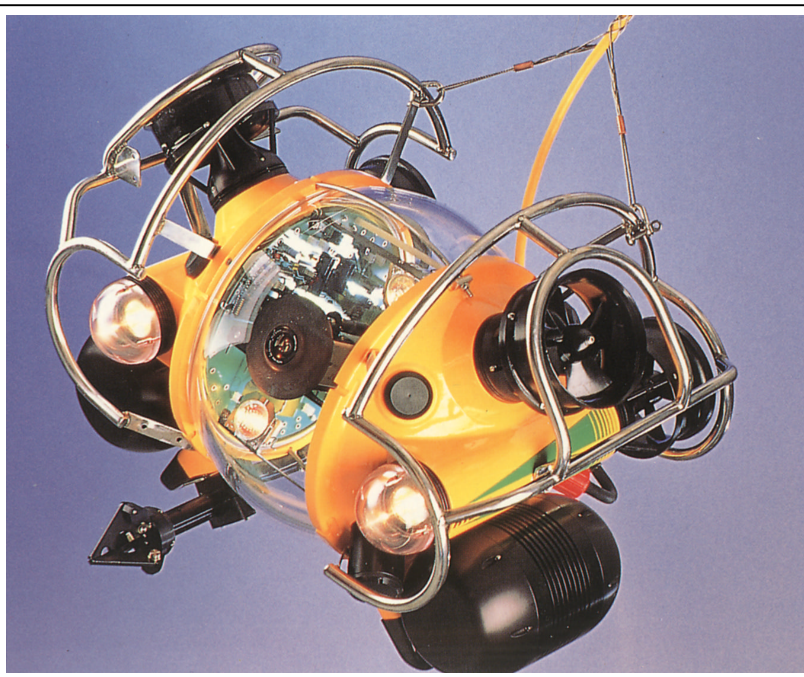
The class of ROV designated "low cost" is only low in cost if compared with its big brothers, however, costs can range from just over $10,000 to over $100,000. The low-end products have been classified for Marine Recreational Use, while the more expensive systems have been used for inland water inspection projects and coastal offshore inspection and observation tasks. Some of the earlier systems were simply video camera housings with thrusters.

The Low Cost ROV (LCROV) first appeared on the market in 1981 with International Submarine Engineering's *RASCL*, which cost about $45,000. In 1984 the infamous *MiniROVER*, built by Deep Sea Systems International was introduced at a price of $28,600. In 1985 Deep Ocean Engineering offered the *Phantom* at about $30,000. By 1990, 35 versions of LCROVs could be counted, being built by 27 different manufacturers with over 500 systems delivered. These costs were a far cry from the $525,000 *Scorpio*s being used extensively at the time. With the downturn of the oil & gas industry in 1986, most eyes turned seriously to the new "professional" LCROVs.



***Quest* Low Cost ROV**

Today's LCROVs are used widely for many tasks including science, search and rescue, dam, waterway and port inspection, training, shipping and nuclear inspection (see Chapter 2, Inland Operations).

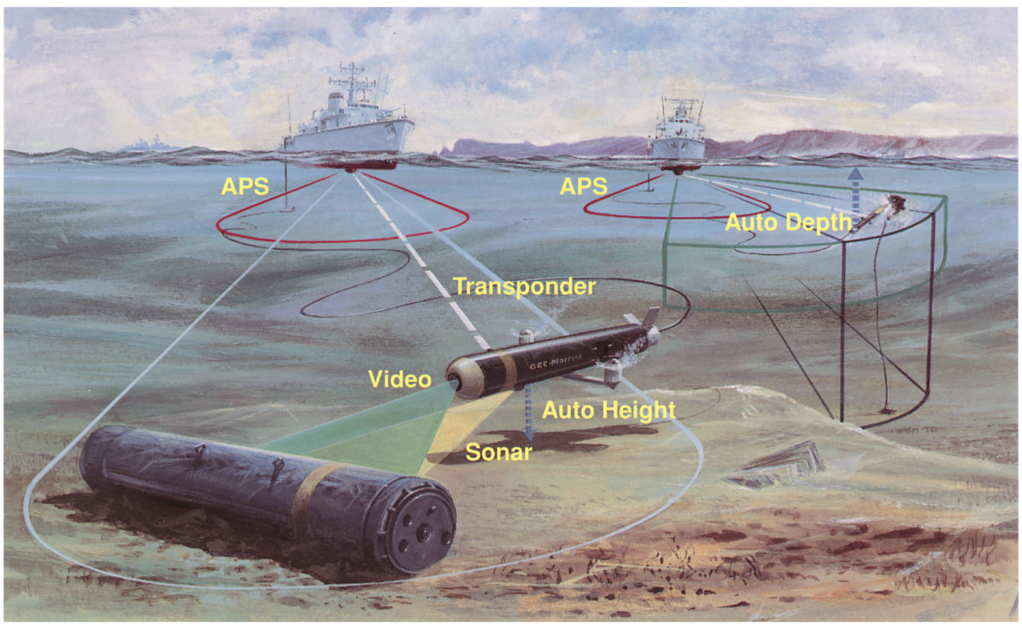


Hydrovison's *HyBall*

"Wire-Guided" ROVs

This unique class of vehicle is used, normally, where the power source can be carried onboard, i.e. batteries, fuel cells, etc. With onboard power, only a thin fiber optic tether is required to pilot and control the ROV. This technology was born from wire-guided torpedoes and expendable fiber optic microcable programs developed within the military arena. Many AUVs use a fiber optic tether to perform testing or to down load information, but it is usually not a permanent attachment

An example of a wire-guided vehicle is the *Archerfish* developed by GEC-Marconi, which will be used as an expendable mine disposal system.



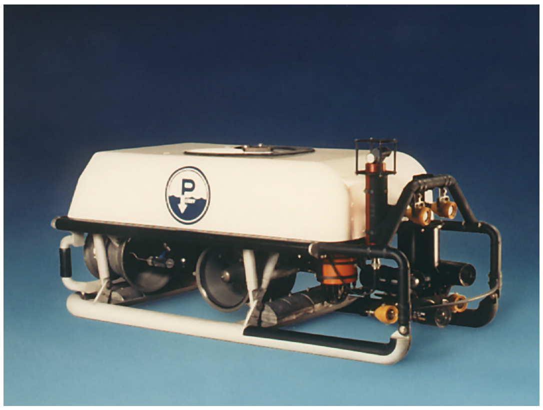
GEC-Marconi's *Archerfish*

The *Archerfish* is deployed from a ship and carries a full length of fiber optic tether aboard. This tether is payed out as the vehicle transits to its target. The vehicle is guided to the target area by becoming a target itself on the ship's sonar. Then, using its auto height or auto depth mode, it locates the specific target via its own sonar or video system. A small warhead on the vehicle is detonated close to the mine eliminating the threat.

These vehicles could be used for many applications, including scientific and commercial, where limited duration and small size are considered positive features.

High Capability Electric ROVs

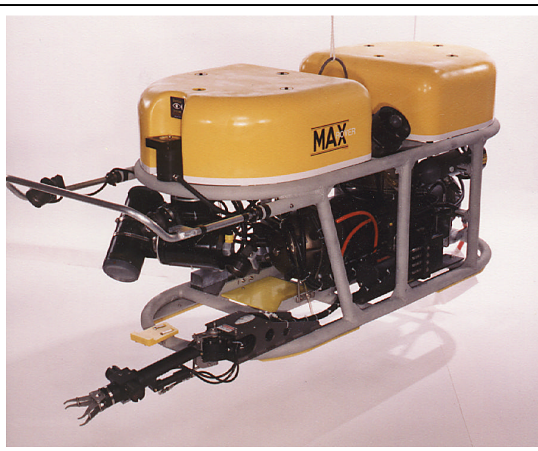
Although ROVs like the infamous Perry *RECON* vehicle have been around for some time (over 50 produced), their technology limited them in both depth and performance. A new class of ROV was born less than five years ago, which although small and electric, is not necessarily low cost and can approach the $500,000 mark. These new vehicles feature the latest in technology from Brushless DC motors (thrusters) to PC-based control systems and fiber optic telemetry systems. Electrically operated vehicles can be made to go 20,000 feet (6,096 meters) with much less power required to operate them at depth. The ability to do heavy work is still not possible with the electric ROVs, primarily limited by the needed electro-hydraulic design nature of modern manipulator and work systems, but they can still perform many tasks at a much lower cost.

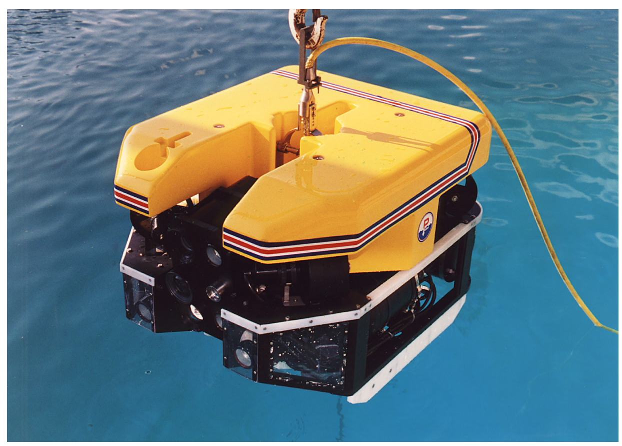


Perry Tritech's *RECON* (above)

Vehicles like the Perry Tritech *Voyager* are very capable inspection systems using the state-of-the-art in fiber optic telemetry and control systems. ROVs like the Deep Sea Systems International *MaxROVER* offer increased power and moderate work capabilities to depths of 9,842 feet (3,000 meters) at a fraction of the cost of electro-hydraulic systems.

Deep Sea Systems International's *MaxROVER* (below)





Perry Tritech's *VOYAGER* (above)

Electric vehicles have gained popularity with the military and science markets due primarily to their quiet operation. In addition, the work requirements for military and science are, in most cases, not as complex when compared to ROVs used for oil and gas operations.

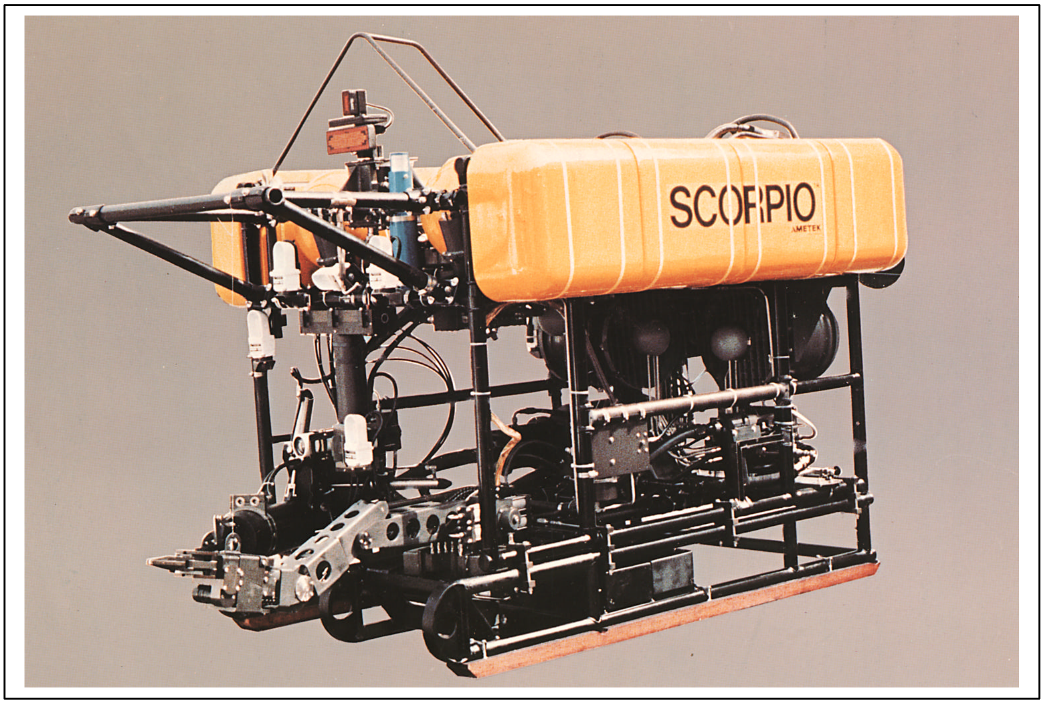
Electric ROVs							
Manufacturer	**Name**	**Size LxWxH-m**	**Depth-m**	**Power-hp**	**Wt.-kg**	**Payload-kg**	**Thru Frame**
Perry Tritech Inc.	Voyager	1.07x0.81x0.66	610-1500	7.5 KVA	182	15.5	n/a
	Scout	0.64x0.62x0.66	250	n/a	115	15	n/a
	Spirit	0.63x0.62x0.74	610	n/a	95	15	n/a
Deep Sea Systems Intl	MaxRover Mk1	2.23x0.9x1.21	1000	n/a	635	80-90	n/a
	MaxRover Mk2	2.23x0.9x1.21	2000	n/a	750	80-90	n/a
	MaxRover Mk3	2.23x0.9x1.21	3000	n/a	750	80-90	n/a
Sub-Atlantic Limited	Apache	0.85x0.55x0.55	1000	n/a	140	25	n/a
	Cherokee	1.33x0.8x0.8	1000	n/a	240	50	n/a
	Comanche	1.63x1.0x1.0	1500	n/a	460	150	n/a
Benthos	EROV	0.5x0.46x0.39	46	n/a	24	2.3	n/a
	MiniRover Mk2	0.86x0.5x0.42	305	n/a	34	3.6-5.4	n/a
	Openframe	1.42x0.84x0.71	304-915	n/a	226	45	n/a
	SeaRover	1.42x0.69x0.65	304	n/a	80-91	7.0-10	n/a
							n/a
Deep Ocean Engrg.	Firefly	0.19x0.15x0.36	46	n/a	5.4	1	n/a
	Phantom 150	0.64x0.34x0.27	14	n/a	14	3.6	n/a
	Phantom 300	1.02x0.54x0.45	100	n/a	34	3.6	n/a
	Phantom DHD2	1.4x0.65x0.65	600	n/a	86	11	n/a
	Phantom DS4	1.73x0.91x0.71	610	n/a	95	14	n/a
	Phantom HD2	1.4x0.65x0.59	300	n/a	73	9	n/a
	Phantom HD2+2	1.4x0.69x0.67	300	n/a	96	9	n/a
	Phantom S4	1.53x0.85x0.66	304	n/a	98	14	n/a
	Phantom Ultimate	1.81x1.17x0.97	610	n/a	363	45	n/a
	Phantom XTL	1.08x0.53x0.46	150	n/a	45	5.9	n/a
	Super Phantom 2	1.52x0.84x0.58	305	n/a	68	10	n/a
Hydrovision	Hyball	0.48x0.53x0.53	300	n/a	42.5	4	n/a
	Offshore Hyball	0.57x0.77x0.57	300	n/a	60	5.0-6.0	n/a
	Super Nufo	1.35x0.95x0.87	1000	8.8 KVA	494	2.0-10	n/a
Racal Technotransfer	Sea Pup	1.1x0.75x0.85	1000	15 kW	350	n/a	n/a
Bofors/SUTEC	Sea Twin MkII	2.1x1.3x0.7	500	n/a	340	n/a	n/a
Seaeye Marine Ltd.	Seaeye 600 DT	1.0x0.76x0.58	300	n/a	65	10	n/a
	Seaeye Panther	1.55x1.05x1.12	1250	n/a	310	90	n/a
	Seaeye Surveyor	1.45x0.82x0.82	300	n/a	180	45	n/a
	Surveyor Plus	1.45x0.84x0.83	300	n/a	190	45	n/a
	Seaeye Tiger	0.95x0.70x0.57	600	n/a	130	30	n/a
Mariscope	SPY	0.78x0.90x0.93	300	n/a	50-55	n/a	n/a
Comex Pro	Super Achille	0.72x0.6x0.52	600-1000	n/a	100	5.0-10.0	n/a

Modern Electric ROVs

Medium Sized Vehicles

This medium size class of ROV refers to electro-hydraulic vehicles ranging from 20-100 horsepower typically, which can only carry moderate payloads and have limited through-frame lift capability. These ROVs range in weight from 2,205-4,410 lbs (1,000-2,200 kg) with typical payload capacities in the 220-440 lb (100-200 kg) range. They usually carry a single manipulator but the larger of the class can carry two. Some have the capability of through-frame lift of over 992 lbs (450 kg).

These vehicles comprise the most widely used ROV class, which evolved from the early "eye ball" systems that were used to observe divers working or to perform routine inspections. This class was developed to perform work, carrying one or two manipulators, in high current conditions. The early ROVs developed, like the *Scorpio* and *Hydra* vehicles, are still in operation around the world today. Typical tasks for this class are drilling support, construction support, pipeline inspection and general "call out" work.

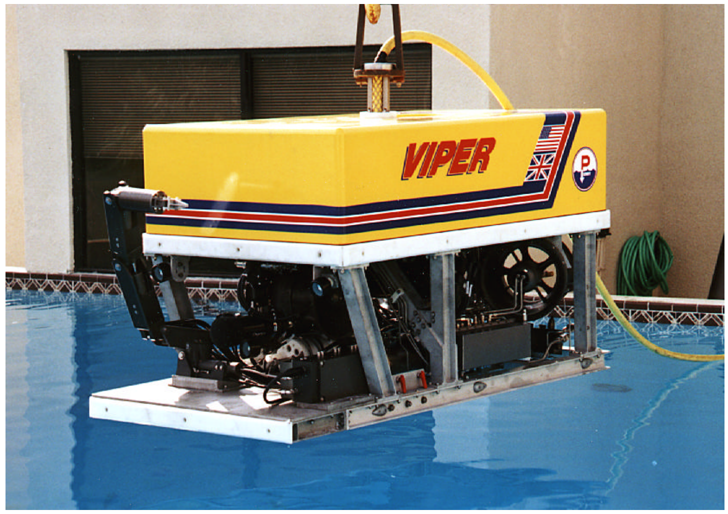


Perry Tritech's (originally AMETEK's) *Scorpio*

Modern systems like the Perry Tritech *Viper*, *Super Scorpio* and *Scorpio Cobra* reflect the latest technology applied to vehicles with the same horsepower as their predecessors, but with much greater reliability and efficiency. Most of these systems fall into the 3,281-foot (1,000-meter) depth capability range due to the fact that until recently, the majority of drilling support work has occurred within this depth.

Vehicles like the *Viper*, weighing in at 2,205 lbs (1,000 kg), replaced the *RECON* providing a more powerful, high thrust, electro-hydraulic platform capable of working in 3-knot or greater currents.

Perry Tritech's *VIPER*



The larger ROVs such as the *Scorpion* and *Cobra* feature 75 hp. and a much-increased work and payload capability while still working at the 3,280 foot (1,000 meter) mark.

Medium ROVs							
Manufacturer	**Name**	**Size LxWxH-m**	**Depth-m**	**Power-hp**	**Wt.-kg**	**Payload-kg**	**Thru Frame**
Oceaneering	AIS	2.14x1.2x1.38	1000	n/a	1500	500	n/a
	Hydra	1.8x1.2x1.3	1000-2500	20-40	862	91	n/a
	Quantum	2.16x1.22x1.32	2516	75	1453	136	n/a
	Magellan 160	2.5x1.5x1.5	1000	60	2041	91	n/a
SubSea Offshore	Examiner	2.0x1.95x1.8	500-2000	75	1700	100	9.8-tons
	Pioneer	1.65x1.65x1.85	1525	75-120	1800	91	n/a
	Eagle	2.0x1.95x1.8	500	75	1700	50	
Hydrovision	Rigworker Mk IV	2.1x1.4x1.5	1000	50	1650	220	n/a
Perry Tritech	Scorpio Cobra	2.54x1.5x1.45	1000-1500	75	1850	204	1500 kg
	Scorpion	2.03x1.4x1.14	600-1000	75	1367	114-204	454 kg
	Viper	2.06x1.04x1.67	1000	25	1000	170	n/a
	Super Scorpio	2.5x2.5x1.9	1000	62	2100	100	400 kg
	Scorpio	2.6x1.829x1.626	1000	57	2200	181	n/a
Racal Techno Transfer	Seal	1.5x1.0x1.0	600	50	850	80	n/a
	Sealion Mk II	2.15x1.4x1.56	1000	100	1750	200	700 kg
	Sealion Mk II V	2.2x1.4x1.6	1000	100	1800	200	n/a
Slingsby Engineering	Spartan	2.5x1.58x1.43	1000-2000	75	to 1980	65-95	1000 kg
	Trojan	2.2x1.6x1.6	1000	40	1800	91	2.1-tons
Harbor Branch Ocean.	Cord III	1.52x1.02x1.02	1067	25	544	68	n/a
Seatec Underwater	Double Dutch	1.9x1.7x1.7	300	16.5	450	200	n/a

Medium Class ROVs

Large Sized Vehicles

This class of vehicle can be broken down by depth capability and horsepower and represents the class of ROVs being used for current deepwater operations to 8,202 feet (2,500 meters) ranging from 100-250 horsepower and having through-frame lift capabilities to 11,025 lbs (5,000 kg), the distinguishing feature between medium and large ROVs. The vehicles range in weight (without work packages) from about 4,410-14,333 lbs (2,000-6,500 kg).

With new requirements to perform subsea tie-in operations on deep-water installations and to carry very large diverless intervention systems, this class of ROV has become very large, powerful and capable of carrying and lifting large loads–thus the term "heavy work class vehicle" has been adopted by the industry. These vehicles may stand over 8 ft (2.4 m) tall when a tool package has been installed underneath the ROV.

Perry Tritech's *TRITON XL*

New Generation ROVs

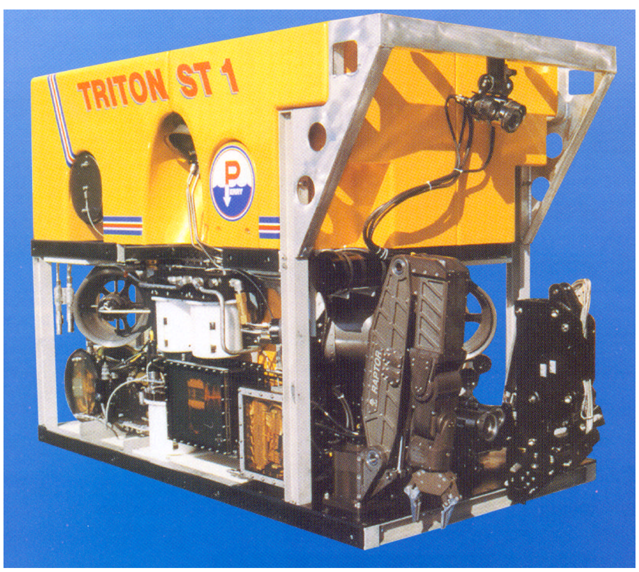
This class is represented by a whole new effort toward building work class ROVs for the oil and gas industry, with capability to perform work tasks to 9,842 ft (3,000 m). These vehicles are retaining the power and lift capabilities of the large systems, but are being built into smaller frames while using more advanced technology aimed at keeping the umbilical size to a minimum. What distinguishes these ROVs form the "ultra-deep" systems is that, unlike the deep diving ROVs that carry only minimal power to minimize umbilical size, this new class carries between 75-100 hp aboard. This is a work class of vehicles that must have the power to perform heavy work at great depths.

Just as the ROV manufacturers were gearing up for the oil and gas industry’s move into deepwater (1986) the price of oil dropped to a devastating $10 per barrel, thus delaying the need for the technology. But now as exploration is being carried out in depths to 12,000 feet (3,658 meters) and production in depths of over 6,000 feet (1,829 meters), the need for new and advanced technology has returned.

Large ROVs							
Manufacturer	**Name**	**Size LxWxH-m**	**Depth-m**	**Power-hp**	**Wt.-kg**	**Payload-kg**	**Thru Frame**
SubSea Offshore	Hercules	2.03x1.73x1.9	2000-3000	120	2200	150	n/a
Hydrovision	Demon	3.65x1.83x1.97	1000-3000	100	2800	300	3-tons
	Diablo	2.65x2.04x1.82	1000-3000	100	2600	300	3-tons
Slingsby Engineering	MRV	1.92x1.5x1.56	600-2000	75-200	to 2250	to 273	5-tons
Stolt Comex Seaway	SCV-100	3.1x1.8x1.8	1000	100	2900	200	5000 kg
Racal Techno Transfer	Sea Serpent		2500	160	2500		5000 kg
Seatec U/W Systems	Seatec RCU 230	3.4x2.3x2.4	1500	230	6500	500	n/a
Perry Tritech	Triton	2.46x1.45x1.6	1000	100	2450	227	3000 kg
	Triton XL	2.46x1.45x1.93	2500	100	3500	500	3000 kg
	Triton XL 250	2.46x1.45x1.93	2500	250	3500	500	3000 kg
Dolphin a.s	Dolphin 2500	2.2x1.5x1.6	2500	100	2500	n/a	6000 kg
Mitsui	Dolphin 3K	2.85x1.96x1.94	3300	54	3700	150	n/a

Large Class ROVs

There is a significant increase in difficulty when extending the operating depth from 8,202 ft (2,500 m) to 9,842 ft (3,000 m). The weight of an armored umbilical becomes critical, having to support its own weight suspended from the surface. Some manufacturers have gone to "cageless" systems (no TMS) and Kevlar umbilicals to deal with this problem. Others have designed the vehicle to use super strong steel umbilicals, applying the latest cable design technology.



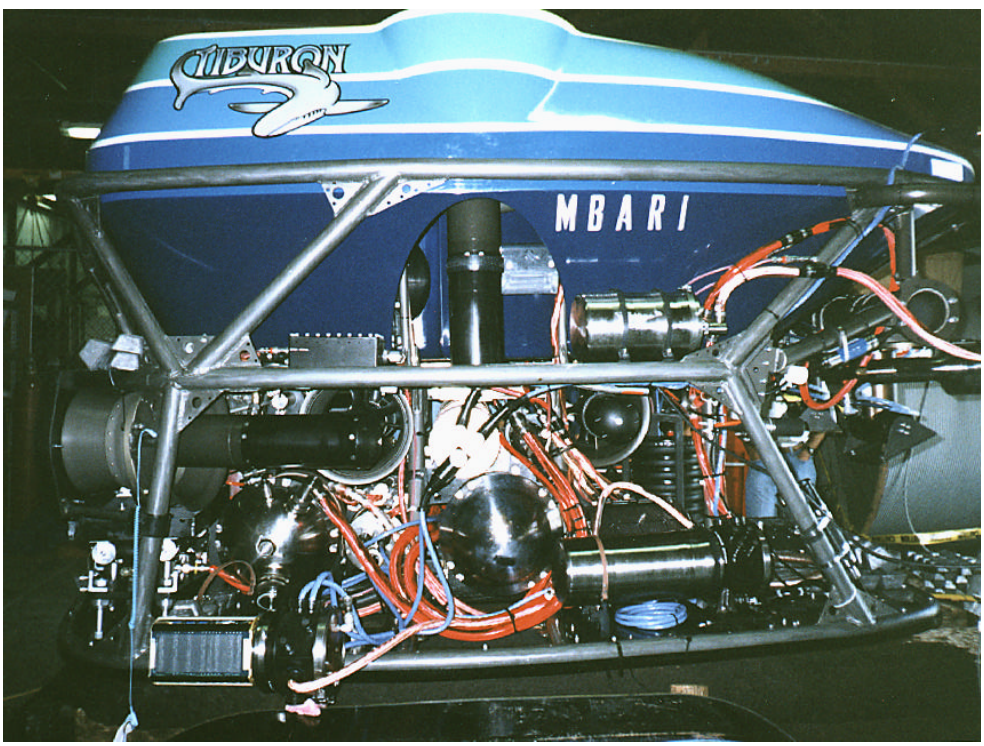
Only a few of these vehicles have been completed, specifically for oil field applications, and include Perry Tritech's *Triton ST* (figure on left), Hitec's *Stealth*, Stolt Comex Seaway's *SCV-3000*, and Oceaneering's *Magnum*. Other manufacturers offer options to 9,842 feet (3,000 meters), however, none have yet delivered a system.

New Generation ROVs							
Manufacturer	**Name**	**Size LxWxH-m**	**Depth-m**	**Power-hp**	**Wt.-kg**	**Payload-kg**	**Thru Frame**
Oceaneering	Magnum	2.4x1.3x1.6	2200-3000	75	1568	160	n/a
Stolt Comex Seaway	SCV-3000	2.5x1.5x1.7	3000	100	3900	200	5000 kg
Perry Tritech	Triton ST						
Hitec Subsea AS	Stealth	3.0x1.7x1.7	3000	108	2800	200	2000 kg
	HiROV 3500	2.5x1.6x1.6	3500	100	2700	200	2000 kg

New Generation ROVs

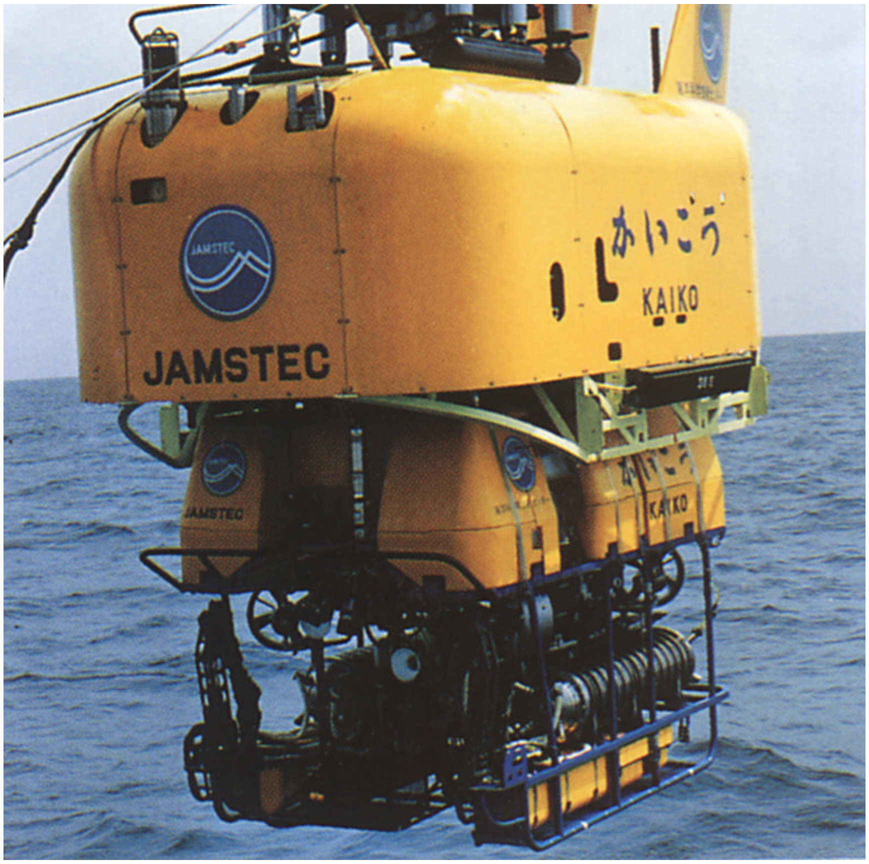
Ultra-Deep Vehicles

This class of vehicle is represented by those special-built ROVs with depth capabilities of 13,123 feet (4,000 meters) and beyond. These vehicles tend to be lower in power to keep umbilical sizes small and are used primarily for deep ocean research, search and salvage missions. For such missions, ultra-deep ROVs do not require much power to observe or attach a salvage line.



Monterey Bay Aquarium Research Institute's (MBARI) *Tiburon*

Many of the ultra-deep systems are designed for science. A scientist can observe life in the very deep ocean for extended periods of time with the use of the ROV.



Mitsui's *Kaiko*

Other ultra-deep-water systems have been developed by the military to perform various missions including the salvage of important assets (see Chapter 2 for Military ROVs).

Subsea International's *Hammerhead*

Other commercial ROV systems have been developed for extremely deep work such as deepwater pipeline repair and salvage operations (see Chapter 2).

Ultra-Deep ROVs							
Manufacturer	**Name**	**Size LxWxH-m**	**Depth-m**	**Power-hp**	**Wt.-kg**	**Payload-kg**	**Thru Frame**
SubSea	Hammerhead	2.99x2.54x2.18	5000	150	4536	907	n/a
International							
Oceaneering	Magellan 725	2.4x1.5x1.4	7000	25	2041	544	n/a
	Millennium	3.0x1.5x1.7	>3000	150	1932	341	n/a
	Magellan 825	3.2x1.4x2.0	8000	25	3000	n/a	500 kg
MBARI	Tiburon	2.7x2.2x2.0	4000	20	3090	100	n/a
	Ventana	2.54x1.48x1.68	4000	30	2338	170	n/a
ISE	Hysub 5000	2.54x1.48x1.68	5000	30	1986	91	n/a
Ifremer	ROV 6000	3.15x2.15x1.8	6000	20	3700	170	n/a
	Victor 6000	3.1x2.1x2.8	6000	n/a	4200	600	n/a
Woods Hole	Jason	2.2x1.1x1.2	6000	n/a	1200	50	n/a
Oceanographic Inst.							
Mitsui	Kaiko	3.1x2.0x2.3	11000	n/a	5600	150	n/a
Okeangeofizika	RTM 6000	1.4x1.2x0.7	6000	n/a	400	7	n/a

Ultra-Deep ROVs

As shown in the previous sections, there is a wide range of ROVs available, from shallow water to the ultra-deep systems. One of the most significant points, however, is the number actively being used for different applications. While many are used for academic applications, the offshore arena is by far the most active, with orders of magnitude more vehicles working daily.

Untethered, Autonomous Underwater Vehicles

The brief history of Autonomous Undersea Vehicles (AUVs) has been an interesting one. Deemed by the international ocean community (other than the military) as too high-tech and high-risk for development, it has turned its back on AUVs for many years. AUVs were being developed to test subsystems–the building block approach. This meant that the AUVs themselves were nowhere near capable of actual missions. They were intended to test components of the AUVs that would ultimately be put into an AUV of the future. But that has changed. Today, developers are designing and building AUVs to perform specific tasks, not for the sole purpose of testing subsystems.

In the 1980s, the military community, believing that AUVs were of strategic importance as stealth reconnaissance platforms, poured hundreds of millions of dollars into a few programs to develop large, sophisticated AUVs. The first major military AUV program was awarded to Draper Labs, which built at least two 44-inch (112-cm) diameter AUVs to demonstrate various missions. It was stated that these vehicles cost over $9 million each to develop. Only a few companies invested the money to develop their own AUVs such as Lockheed Martin's/Perry Technologies' *MUST Lab* and Raytheon's (formerly Applied Remote Technology) *XP-21*. The *MUST Lab* was developed at a cost of over $4 million, while *XP-21* cost about $1 million to develop.

Because of the potential of significant Navy funding in the future, a trend arose to design 21-inch (53-cm) diameter AUVs that could fit in a Mk 48 equipped submarine. This was a futile attempt and only recently has the US Navy funded a program to develop a sub-launched AUV system. This program was awarded to Northrop (formerly Westinghouse) in 1994. Known as the Near Term Mine Reconnaissance System (NMRS), the vehicle is intended as a "stop gap" system that will later be replaced by the Long Term Mine Reconnaissance System (LMRS), worth about $1.5 billion. To win the NMRS contract, Westinghouse funded Applied Remote Technology to quickly build the little talked about demonstration AUV (name unknown), which was successfully launched and operated from the SSN 637-class nuclear submarine *Hammerhead*.

Scientists had been playing with laboratory versions of AUVs for years, primarily at the subsystem level, never quite putting together a complete system. The ocean community again accused the technology of being "a solution looking for a problem." In some ways this was true as many of the vendors were looking to make money rather than to find useful applications for AUVs.

Internationally, AUVs were being built, and many reported to be successful such as the AUVs launched by the former Soviet Union. The UK launched at least one AUV as well. These AUVs were also funded by the military, however, the nature (and cost) of these vehicles did not lend themselves to commercial applications. Meanwhile, in the background, academic organizations such as MIT Sea Grant and Florida Atlantic University began to develop low cost, small AUVs ignoring the doubts of the major defense companies.

These new AUVs were not only small, thus easy to launch from small boats, but they were also smart and capable systems. Their small size helped to speed their development because many trial runs could be made at little cost and in easy to reach coastal or inland waters. These 6- to 7-ft (1.8- to 2.1-m) long vehicles cost about $50,000 to $100,000 to develop, orders of magnitude less than their bigger predecessors.

In about 1994, the Office of Naval Research, which funds academic institutions almost exclusively in this area, became very interested in these vehicles for purposes of conducting ocean research of various types. This lower level of funding allowed the academic institutions to pave the way for the commercial AUV. Even the big defense contractors realized the potential for these small, low cost vehicles, as essentially disposable minehunting vehicles and began to purchase pieces of the technology to develop inexpensive versions of the vehicles they could call their own.

Since then, many organizations around the world have produced AUVs for a wide array of missions. Not until the late 1990s has the oil and gas industry begun to look at AUVs as a way to perform work at a much lower cost than ever before. The reason for the new acceptance of AUVs is due to the way they have been proposed to operate–in a semi-autonomous mode. One of the biggest objections to AUVs has been related to its similarity with a torpedo when out of control. However, the thought of operating remotely, without a tether, by an acoustic link has made the AUV a very practical solution for many underwater tasks. In fact, it eliminates the one major drawback to ROVs operating in deep water. Control by acoustic link is reliable, just slower. Companies like Datasonics, who build acoustic links, have stated that high data rate communications are just around the corner. This will become more important when AUVs begin to perform tasks more complex than search or survey operations.

An AUV using bi-directional acoustic communications and data transmission was first demonstrated by the US Navy's Advanced Unmanned Search System (*AUSS*) which began development in about 1978. The *AUSS* turned out to be one of the most successful AUVs of its time with 135 missions completed, the deepest to 12,000 feet (3,658 meters). Funding was eliminated in FY 1992 due to restructuring of the Navy's UUV programs; *AUSS* operations were discontinued and the vehicle "mothballed."

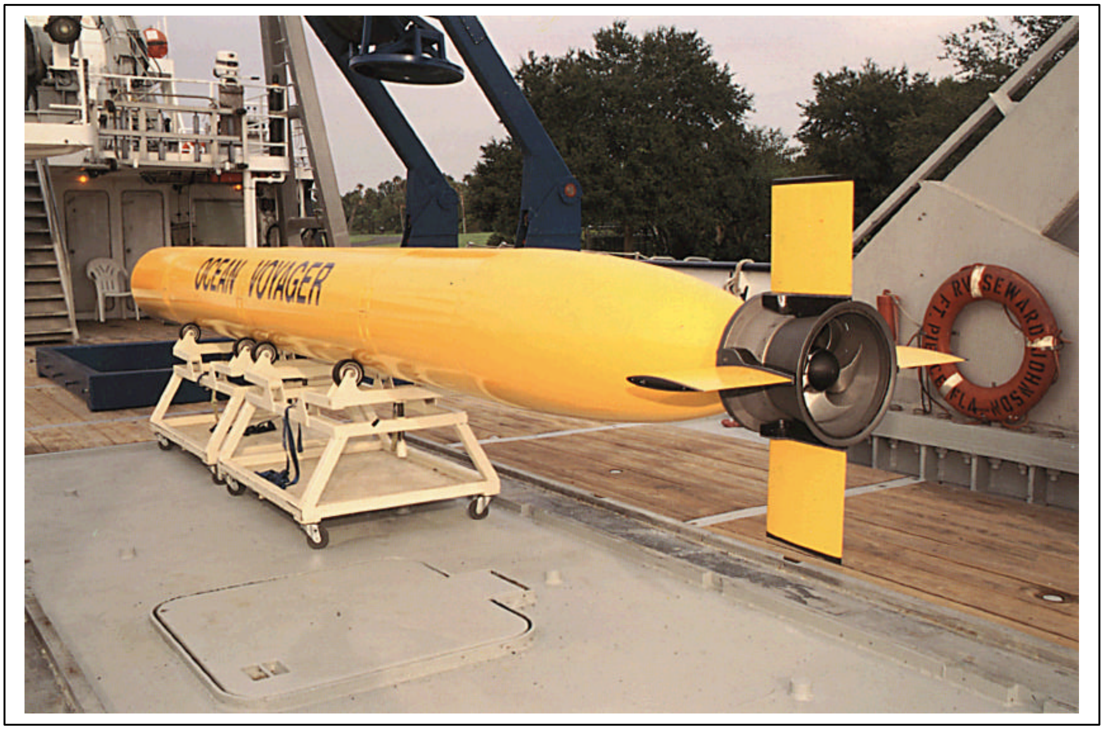
Today, AUVs such as Norway's *Hugin* are to be operated in nearly the same manner as *AUSS*, i.e. via an acoustic link. *Hugin* represents the first system funded by an oil company (Statoil) for operation in the oil fields.

Test Bed AUVs

In the early days of AUVs there was a perceived market for a platform from which future technology could be tested and demonstrated. Thus the first AUVs were produced, as intended, for only supervised operations in well-known areas. A few of these systems are described below:

Ocean Voyager I & II

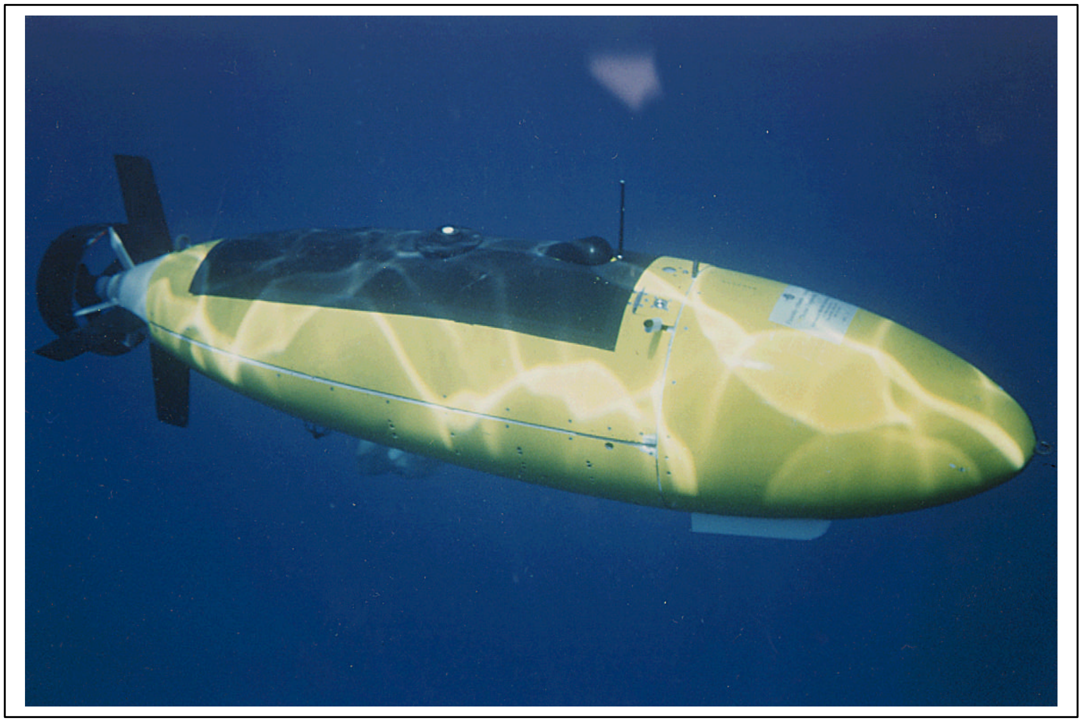
Ocean Voyager I began as a joint effort between Florida Atlantic University (FAU) and Lockheed Martin's Perry Technologies. Later, Harbor Branch Oceanographic Institution joined in to complete the vehicle. Although the vehicle was about 98 percent complete, its size and perceived operational cost caused it to be abandoned for *Ocean Voyager II* a smaller, less expensive AUV.



Harbor Branch Oceanographic Institution (HBOI) and Florida Atlantic University's (FAU*) Ocean Voyager I*

Ocean Voyager II was designed and built by students at FAU as a senior class project in the Fall of 1992. The success of the vehicle allowed additional funding to be obtained and the vehicle became fully operational. The *Ocean Voyager II*, when completed, was delivered to the University of South Florida (USF) for integration of an optical sensor package used to ground truth data from satellites in the shallow coastal environment.

The vehicle has been operational since 1994 and has been used to test CHIRP side scan and sub-bottom sonars, video cameras and long baseline (LBL) navigation techniques. *Ocean Voyager II* provided the foundation for the development of the *Ocean Explorer*, FAU's next generation AUV.



Florida Atlantic University's *Ocean Voyager II*

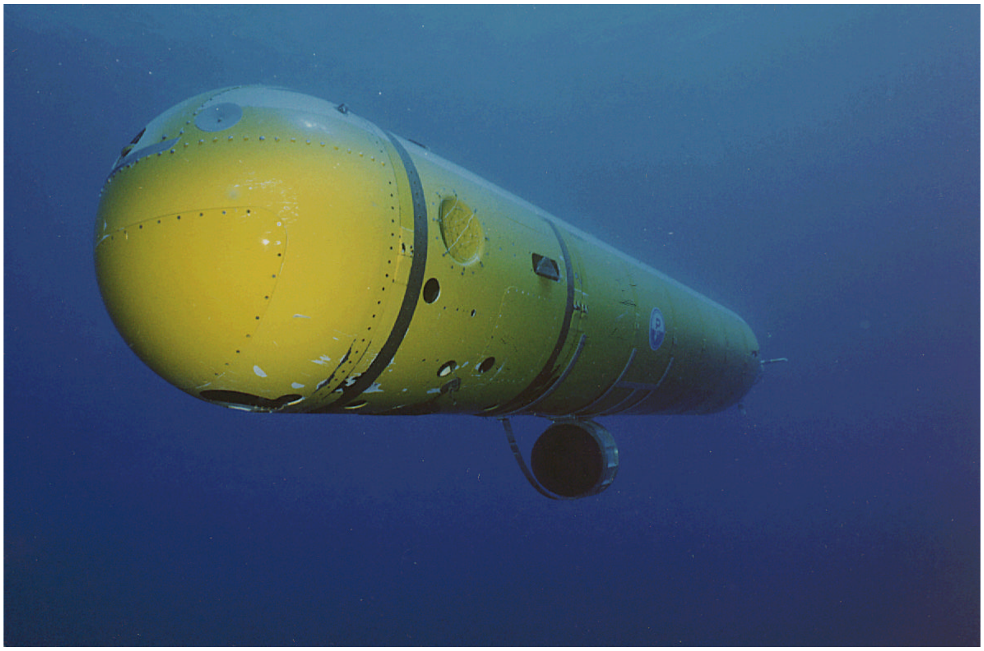
EAVE III

One of the earliest AUVs to be launched was *EAVE III*, designed as a testbed vehicle for testing control systems and algorithms. Operated by the Marine Systems Laboratory of New Hampshire, the ROV look-alike vehicle was completed in 1987. It was capable of diving to about 650 feet (198 meters).

MUST Lab

The Mobile Undersea Systems Test (*MUST*) Laboratory was developed by Martin Marietta and operated by Perry Technologies. Credited with being the world's largest AUV, its size and weight now work against itself for outside funding. *MUST* is 30-ft (9.1-m) long and 54-in (137 cm) in diameter, weighing in at 19,500 lb (8,843 kg). The vehicle requires a support ship of about 190 ft (58 m) or greater for operations offshore. Perry Technologies eliminated this expense by towing it offshore and operating from smaller ships.

MUST's primary advantage is its 1,500 lb (680 kg), 53 cubic foot (1.5 cubic meter) dry payload capability plus additional wet payload as well. This configuration was deemed critical by the developers, since it was intended to carry advanced military electronics that the Navy had designed for 19-inch (53-cm) racks aboard submarines or other military craft.



Lockheed Martin's *MUST Lab*

Its operating depth is 2,000 ft (610 m) with a transit speed of up to 8 knots (14.8 km/hr). The AUV was operated using lead acid batteries for the most part as no long missions were ever afforded it. It is capable of an endurance of 8 hours at full power or 24 hours at 5 knots (9.3 km/hr). *MUST* also adopted the *AUSS* design of a nose recovery buoy that could be snagged with a boat hook and attached to a recovery line on the launch and recovery system, which was similarly an AUSS ramp type system.

First put to sea in 1989, *MUST* made over 100 dives and is still being used by Lockheed Martin to test advanced systems such as the propulsion unit for the Navy's newest vehicle, the Remote Minehunting System (*RMS*). *RMS* is a semi-autonomous, semi-submerged vehicle controlled at the surface by an RF link.

***MUST Lab* during at-sea launch**

XP-21

The first attempt at capturing what appeared to be a huge market within the military, was with the *XP-21*. Designed and built by Applied Remote Technology (ART), the vehicle was less than 22-ft (6.7-m) long and 21 in (53 cm) in diameter–the size of a Mk 48 torpedo.

XP-21 was a modular AUV in that sections could be added to increase its length from the minimum 18 feet (5.49 meters) to a maximum of 35 feet (10.7 meters). It weighed 1800 lb (816 kg) in air and could dive to 2,000 feet (610 meters). The *XP-21* had 10 kWh of power from lead acid batteries. It had an endurance of 5 hours with lead acid batteries and a calculated endurance of 48 hours with the fuel cell.

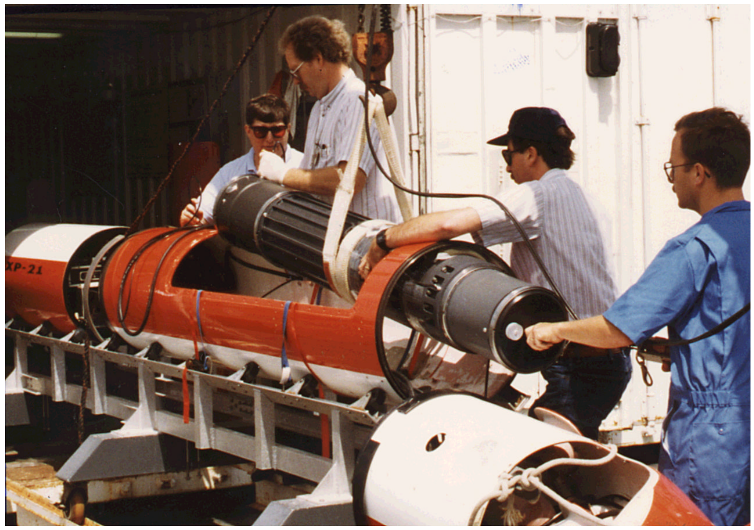
Raytheon's *XP-21*

DARPA was interested in the concept of launching an AUV from a submarine for reconnaissance and mine countermeasure missions. Officially the program evolved into the Submarine Off-board Mine Search System (SOMSS). Contractors were promised competition in a potentially well-funded program. However, budget cuts put the program on indefinite hold, along with ending the Navy's successful *AUSS* program.

This new funding environment in the Pentagon left AUV developers like ART with a platform for hire, but without much funding to keep them going. When Raytheon bought ART from General Dynamics, they needed the technology to win the Mk 30 Mod 2 ASW Training Target–a 21-inch (53-cm) AUV. After they won the program, they shut down ART and put *XP-21* in the closet.

XP-21 was used by DARPA to test the Alupower aluminum/sea water fuel cell at a very low funding level, while Loral and other giants got most of the funding for fuel cell development. It was also used as a test platform by other vendors for several years before the Raytheon acquisition.

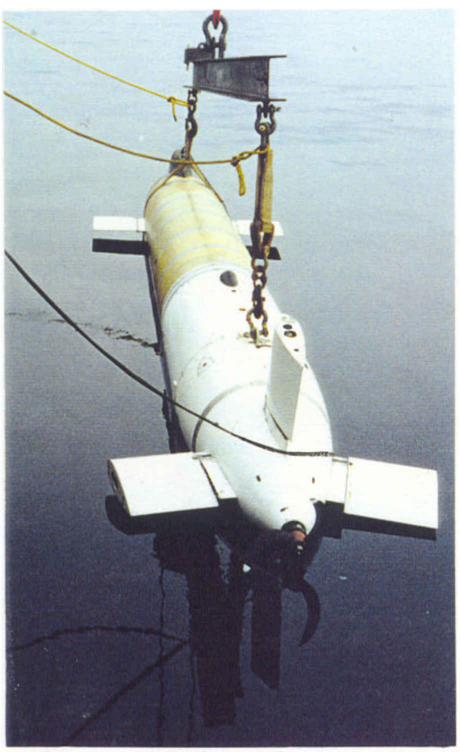
One of the *XP-21*'s most dramatic demonstrations was the integration and use of a laser line scan system (see adjacent figure), a state of the art sea floor imaging system.



XP-21 Receiving Laser Line Scan System

ARCS

International Submarine Engineering began the development of their first AUV, *ARCS*, in 1981 for the Canadian Hydrographic Service. *ARCS* is 21 ft (6.4 m) long and 27 in (69 cm) in diameter. It has a displacement of 4,050 lb (1,837 kg). Top speed is 5 knots (9.2 km/hr) and its range is 20 nm (37 km) with a lead acid battery and 125 nm (232 km) with its 10-kWh nickel cadmium battery. *ARCS* uses a Datasonics acoustic telemetry link, vehicle control is via a 68030 microprocessor and navigation is by a Honeywell 726 MAPS inertial navigation system and EDO 3050 Doppler sonar. In 1996 a Seabird CTD was integrated and demonstrated.



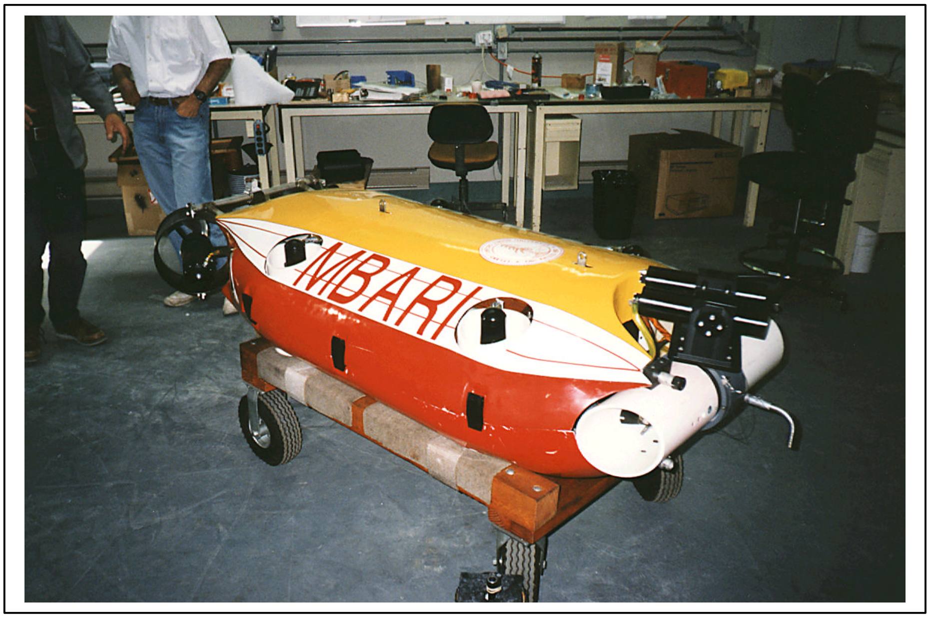
ARCS was to be used for hydrographic surveys under the ice. The operational prototype was completed in 1986 but there was no longer a requirement for under ice operations. In 1988 the Canadian Navy acquired the vehicle for AUV development activities. Between 1989 and 1992, extensive hydrodynamic testing was undertaken with *ARCS* as a beginning to the development of the larger *Theseus* AUV. In 1994, a 70-kWh aluminum-oxygen fuel cell developed by Fuel Cell Technologies was demonstrated in the vehicle and a 36-hour continuous run was documented.

Otter

Monterey Bay Aquarium Research Institute (MBARI) has developed an AUV called *OTTER* (Oceanographic Technologies Testbed for Engineering Research). The vehicle exists primarily as a development tool for optical systems to be used to image the sea floor and to perform video mosaicking.

MBARI has developed an approach to enable the task of video mosaicking along unconstrained vehicle paths. This technique reduces the image errors, which propagate through the image chain, by using the theory of optimal estimation and smoother-follower techniques to identify and remove them. To date this vehicle has only been operated in a test tank environment.

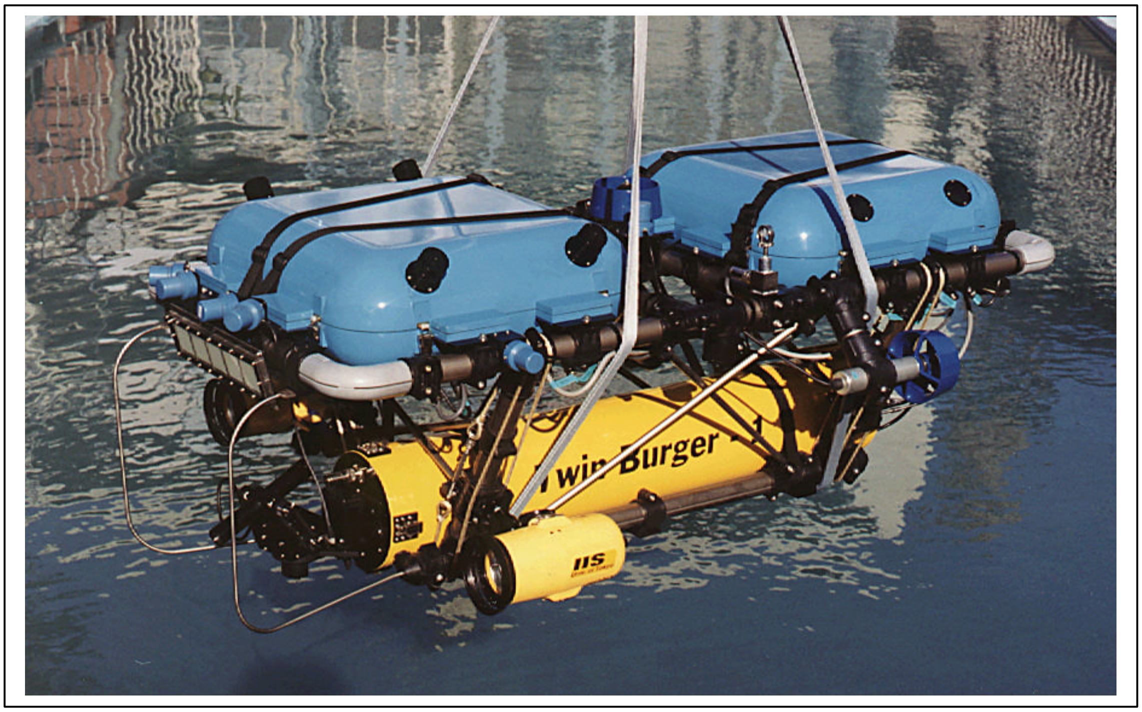
MBARI's *Otter*



Twin Burger

The *Twin Burger* was developed in 1992 at the Institute of Industrial Science, University of Tokyo and sponsored by the Toyota Motor Corporation. It was developed as a test bed for software development and uses 14 Insmos transputers as an onboard multi-processor system. A distributed Vehicle Management Architecture was developed to generate a sequence of behaviors for commanded missions while handling the hardware interface in real time. The vehicle, looking more like an ROV than an AUV was designed for performing complex stationary tasks rather than cruising tasks.

Twin Burger is 5 ft (1.5 m) long, 2.8 ft (0.9 m) wide and 1.7 ft (0.5 m) high. It weighs 265 lb (120 kg) in air and dives to about 164 ft (50 m). Propulsion is by five 40-Watt dc motor driven thrusters. It carries two batteries (25 volt and 28 volt) that provide 10 amps each.



Institute of Industrial Science's *Twin-Burger*

Search & Survey

AUSS

The US Navy's Advanced Unmanned Search System (*AUSS*) is discussed first as it will illustrate how AUVs are operated in the semi-autonomous mode.

Although *AUSS*' technology is becoming outdated, the basic configuration is the same as modern AUVs. The technology itself has gotten less expensive, more powerful, faster, lighter, smaller, etc., making the AUV more practical than ever before.

The primary advantage of *AUSS* over conventional towed search systems is its ability to hover. Secondly, there is no umbilical to add drag, maneuverability and reliability problems to the operation.

AUSS is a 17 ft (5.2 m) long, 31 inch (79 cm) diameter vehicle that weighs 2,800 lb (1,270 kg). The structure of *AUSS* is still considered to be state of the art consisting of a cylindrical pressure hull constructed of graphite epoxy and fitted with titanium hemispherical endbells. All external pressure housings are titanium. All of the buoyancy required is provided by the pressure hull, even with the forward and aft compartments flooded. The fairings are fabricated of Spectra 1000, which has a specific gravity near that of water.

The vehicle has two 120-VDC (0.75 hp at 1000 rpm) main thrusters aft and two (0.33 hp at 1200 rpm) vertical thrusters for pitch and trim control. The motor controller operates at 40 kHz so as not to interfere with the acoustic link. Movable fins provide vertical control at high speeds. Power is provided by 20-kWh silver-zinc batteries, a source of power used almost exclusively by the Navy due to its high cost. Battery endurance is 10 hours at a maximum speed of 5 knots (9.3 km/hr). A backup battery provides an additional one hour of emergency processor operation if needed.

The objective of *AUSS* is to collect sonar and optical images of the ocean bottom to depths of 20,000 ft (6,096 m). The images are sent to operators on the ship above and are used to make tactical decisions and to supervise the vehicle's operation. An acoustic link operating from 8 to 14 kHz transmits compressed search data at 1200, 2400 or 4800 bps to the surface as well as high level commands from the ship to the vehicle. The vehicle must stay within a 90-degree cone below the support craft to ensure low error rate communications.

A unique subsystem of *AUSS* is EARS, the External Acoustic Relay System, a 4 ft (1.2 m) long, shallow-towed submersible containing a transducer and acoustic link preamp. By towing the device behind the surface ship at depths between 50 to 300 ft (15 to 91 m), the noise generated by the ship is decoupled from the acoustic link.

The vehicle navigates with help from a Doppler sonar and gyro-compass. The vehicle can then be commanded to go to a specific location using Doppler coordinates or can execute preprogrammed search patterns without assistance. Side scan sonar (100 kHz nominal) is also utilized for rapid search of large areas coupled with a forward-looking 100 kHz sonar for closing in on targets discovered during the wide area search along with an additional 267 kHz sonar for obstacle avoidance. An electronic still camera is used to identify targets, both desired and false, by sending compressed images to the surface via the acoustic link. A 35-mm camera is also onboard for taking high-resolution images (see *AUSS* figures in Military section for examples).

The two highest level commands are the side scan search command and the optical photomosaic. In both operations the operator defines a rectangular area of the bottom and the vehicle autonomously proceeds in a square-wave pattern, while continuously transmitting images.

During recovery the nose, connected to 80 ft (24 m) of polypropylene line, is ejected and acts as a recovery buoy. Two ascent weights are made form 36-lb (16-kg) lead forms attached to corrosive link assemblies. In an emergency, the weights can be dropped either by a direct command, timer or finally (after 30 hours) via the corrosive links.

Onboard processors are Intel 80386 vintage mounted in Multibus II card racks. Vehicle software is written in PL/M and runs on the RMK real-time operating system.

The control van is a 40-ft (12-m) ISO container and the launch and recovery system is a ramp type device. Detailed information about *AUSS* can be obtained through NCCOSC Technical Report 1528, November 1992.

Hugin

The *Hugin* program was originally funded by the military for minehunting, submarine offboard sensors, anti-submarine warfare, reconnaissance, and probably for detecting those mysterious intruders in the Norwegian Fjords you are always reading about. The Norwegian Defence Research Establishment (FFI) teamed with Statoil originally to sell the concept of an AUV that could be used for both military and commercial purposes at very high cost savings to the industry. The military was apparently looking for a way to get additional funding to complete the project.

They claim that *Hugin*, in its commercial role as a survey and inspection tool, will replace ROVs for certain tasks such as deepwater seabed mapping and pipeline inspection, and at a fraction of the cost of ROV systems. They also claim that the main advantage of the AUV is that it can get a sonar closer to the seabed resulting in much higher resolution data, while eliminating the umbilical greatly increases its survey speed and maneuverability.

The system has came about because of financing from Statoil's research centre (which determined what the specifications of the vehicle were to be) and the Norwegian Industrial and Regional Development fund. The developers consisted of FFI, Kongsberg Simrad and the Norwegian Underwater Technology Center AS (NUTEC). NUTEC will operate and market the *Hugin*.

The first series of sea trials were completed in June 1998 and were deemed successful. An operational system is scheduled for delivery by the end of 1998 and is probably more of a demonstration unit than anything, with a depth capability of 1,970 ft (600 m). The more advanced systems, which contain a sea water battery, advanced navigation capabilities, a 6,561-ft (2,000-m) depth capability, etc. is only in the planning stage so far. Called *Hugin 2000*, it is planned to be available near the year 2000.

The *Hugin's* main sensor system is Kongsberg Simrad's advanced ES 3000 multibeam echosounder for seabed surveys, which produces an array of 127 beams per ping allowing a swath width of more than 656 ft (200 m) with a resolution of 10 mm.

The vehicle navigates relative to the surface ship via Kongsberg Simrad's super-short baseline positioning system called HiPAP, enabling it to operate as far as 6,561 ft (2,000 m) from the ship. Range accuracy is about 0.7 ft (0.2 m) and bearing accuracy is about 0.2 degrees. Other sensors for navigation include two fluxgate compasses, a Doppler speed log and a 6-degree of freedom motion reference unit.

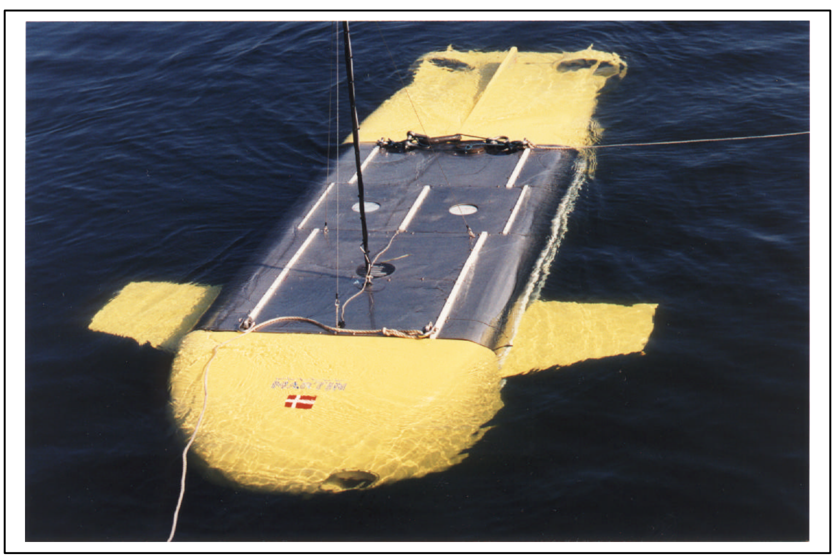
Communications are via three acoustic links: one for command and control, one for data and one for emergency transmissions. The command link can transmit control data from the vessel at a rate of 50 bits/sec and is used to control the vehicle in real time versus preprogramming it for subsea tasks. The data link can transmit the vehicle's position and heading along with summary data from its mission at a rate of 2000 bits/sec. The complete data set is stored on a hard disk aboard the AUV and is capable of storing 36 hours of sonar data.

The entire system including controls, storage and launch and recovery is contained within a 40-ft (12-m) ISO container.

Martin

Maridan of Denmark completed the Martin AUV in 1995 and began sea trials in 1996. The *Martin* is based on a previous prototype AUV called *Marius* (identical in shape and size). This AUV was developed for oceanographic and commercial surveys (e.g. pipeline, cable, pre-construction and bathymetric surveys) to 1,969 ft (600 m) of water. The AUV utilizes a "flat fish" low drag hull design and is large enough to carry survey equipment such as pipeline tracking sensors. *Martin* uses a CAN microcontroller-based network for vehicle control. The navigation and image analysis computer is a VME MC 68040.

Martin is about 15 ft (4.6 m) long, 3.6 ft (1.1 m) wide (excluding its bow planes) and 2 ft (0.6 m) high. Propulsion consists of two main thrusters (45 lb of thrust each) and four tunnel thrusters (three vertical and one transverse). It weighs about 2,200 lb (998 kg) in air. Power is provided by 5 kWh lead acid batteries resulting in a duration of 25 hours and a maximum range of about 48 miles (77 km). Speed range is 2-5 knots (3.7-9.3 km/hr). The vehicle uses a RESON SeaBat sonar for obstacle avoidance, an EDO Doppler Speed log, KVH gyro, Phillips autopilot and pressure gauge for navigation sensors and also carries a video camera. Communications between the vehicle and the surface ship are via a 50 kHz, 200 bps acoustic modem.



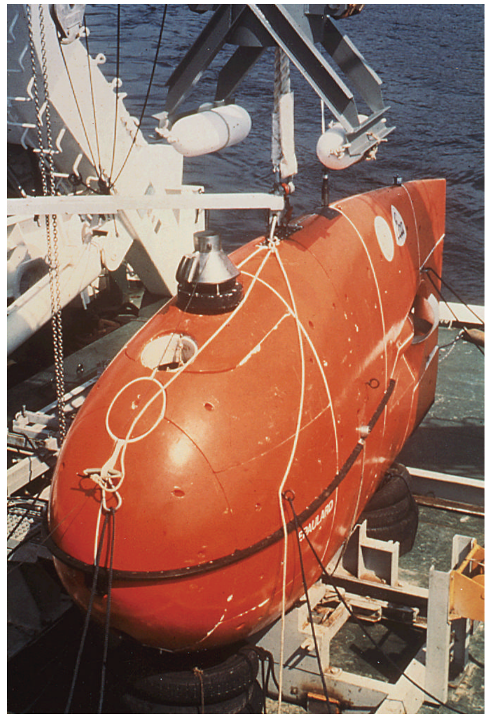
Maridan's *Martin*

Like most AUV systems, the vehicle can be operated in a tethered mode, semi-autonomous mode or fully autonomous. *Martin*, however, uses an interesting communications system concept in the fully autonomous mode consisting of a deepwater acoustic modem that sits on the sea floor and is connected to the surface via a cable and buoy. The buoy has a transmitter that sends back data to the operators by line of sight or via satellite. This data is first down loaded by the AUV. Two-way communications are also possible enabling the operators to download new mission profiles or make changes in the mission without bringing the AUV back aboard ship or to shore. This scheme, and direct communications via acoustic modems, will probably be the preferred method for AUV operation in the near future.

Scientific AUVs

Epaulard

The French *Epaulard* built by ECA was the first acoustically controlled AUV to dive to 19,685 ft (6,000 m). The vehicle weighed nearly 3 tons (3,048 kg) and was 13 ft (4 m) long, 3.6 ft (1.1 m) wide and 6.6 ft (2 m) high. Built in 1981, this AUV was well ahead of its time. The vehicle is now retired and on display at IFREMER.

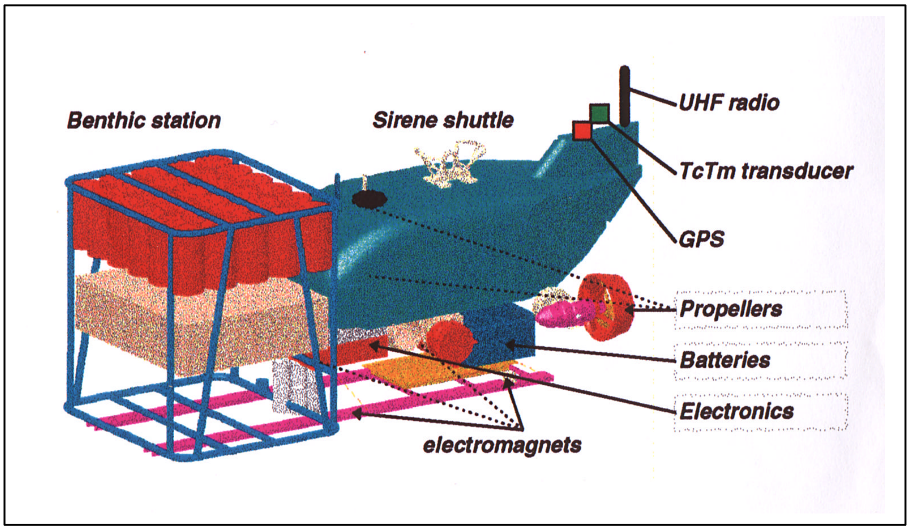


SIRENE Shuttle

SIRENE **(below); ECA's** ***Epaulard*** **(above)**

SIRENE, developed by IFREMER, is designed to land a benthic station with high accuracy in depths to 13,123 ft (4,000 m). The AUV is tele-supervised through a bi-directional acoustic link. It is an 8,820-lb (4 metric ton) free swimming shuttle positioned via a hybrid acoustic long baseline, dead reckoning system aboard the vehicle itself.

The vehicle was built using spare parts from the submersible *CYANA*. It is fitted with two main propellers and a vertical propeller, powered by 120 volt, 185-amp-hr lead acid batteries. Communications are performed through a new 10-12 kHz Chirp, 20 bits/sec, acoustic, bi-directional tele-transmission and a classical UHF radio at 19,200 bits/sec. The vehicle is also fitted with a Brooks altimeter, Depth Cell DC10R depth sensor, Watson AHRS-C303 attitude reference unit, Thomson TSM5740 Doppler and GPS for initialization.



***SIRENE* with Benthic Lab**

The heart of *SIRENE*'s positioning system is an acoustic rangemeter that determines the distance between the vehicle and acoustic transponders. The rangemeter, using absolute references, allows driftless position update using up to 6 beacons. Most systems use threshold detection, while the rangemeter detects up to 10 candidate ranges over a range of about 19,685 ft (6,000 m) maximum. The selection of the best candidate is accomplished by state-of-the-art data association techniques.

Odyssey IIb

In 1991, the first small, low cost AUV (*Odyssey I*) was developed at the MIT Sea Grant College Program AUV Laboratory. It was tested in the waters off New England in 1992 and then deployed off Antarctica in early 1993. In 1994 the creation of the second-generation vehicle *Odyssey II* began, under the sponsorship of ONR. In 1995, as part of the VENTS program, the *Odyssey* dove to depths of over 4,500 ft (1,372 m), fully autonomous, over the Juan de Fuca Ridge. In 1995, four new vehicles were built, again funded by ONR.

This new generation vehicle was named *Odyssey IIb. Odyssey II* was also upgraded to a *IIb* raising the total number to five. In 1996 two *Odyssey IIb* vehicles made 67 dives (with no failures) in the Haro Strait off Vancouver Island, studying the dynamics of frontal mixing.

MIT's *Odyssey* (right)

The *Odyssey IIb* is about 8 ft (2.4 m) long, teardrop shaped and weighs about 365 lb (166 kg). It is rated to a depth of 20,000 ft (6,096 m). It is powered by 3.2 kWh silver-zinc batteries and has an endurance of 12 hours at about 2.7 knots (5 km/hr). The *Odyssey* uses a 68040 computer and carries payloads including CTD, ADCP, cameras and side scan sonar. The *Odyssey IIb* has a component cost of less than $75,000.

Ocean Explorer

Unlike its predecessor, *Ocean Voyager I*, Florida Atlantic University's (FAU) next generation *Ocean Explorer* is built in a modular fashion with a parallel mid-body that allows the vehicle's length and volume to change to meet different mission requirements. This design is funded by ONR, NOAA and the State of Florida.

FAU's *Ocean Explorer*

This AUV uses an extensive intelligent distributed control system called LonWorks via Echelon's Neuron chip for communications between numerous sensors and actuators. All vehicle sensors are connected on a single serial network. Adding devices to the vehicle consists of just plugging into the network. Either a cable or wireless Ethernet links the AUV to the surface vessel. The basic vehicle is 7.5 ft (2.3 m) long, but by adding a parallel mid-body of up to 3 ft (0.9 m) long, increasing the vehicle length to 10.5 ft (3.2 m), a payload volume of 7.5 cubic feet (0.2 cubic meter) can be gained.

There is also payload space available in the nose section for smaller packages and sensors. The batteries, Doppler speed log and control electronics are located in the aft section and are not effected by changes in vehicle length.

Every inch of space has been maximized. The main pressure vessel is surrounded by battery canisters in a radial fashion. Each canister is discharged individually insuring that the Ni-Cad batteries' life is maximized.

Marconi AUV

In the UK, Marconi Underwater Systems in cooperation with Chelsea Instruments and Moog Controls were funded by the Department of Trade and Industry as part of the Wealth from the Oceans Initiative, to develop a research AUV. As far as we know, it had no name except for Research Autonomous Underwater Vehicle. The vehicle obviously grew out of Marconi's experience with torpedoes and was quite sophisticated.

GEC-Marconi AUV

The AUV was about 21 ft (6.4 m) long with a diameter of 21 in (53 cm), but considering the fins that protruded from the 21-in (53-cm) envelope, the diameter was increased to over 35 in (89 cm). This was common in AUVs that might be launched from submarines, but where this option was considered unlikely, designers went for better control at low speeds by using larger fins.

The vehicle weighed just over 2,900 lb (907 kg). The operators claimed an endurance of 36 hours and a range of 186 miles (300 km) with a maximum speed of 5 knots (9.3 km/hr). Depth capability was 1,000 ft (305 m). The vehicle was fitted with a side scan sonar and a Chelsea oceanographic instrumentation suite.

The vehicle was completed in 1992 and completed sea trials. In 1993 it was used for scientific experiments under the edge of the Polar Ice Cap.

Autosub – 1

Autosub-1 is the UK's newest AUV, a result of a £5 million Natural Environmental Research Council (NERC) technology project that began in 1988 with the aim of developing a national capability in AUVs for ocean science. *Autosub-1* is the first of a projected range of AUVs. The vehicle made its first dive in 1996 and since then has made over 70 successful autonomous practice missions and demonstrations. It is operated out of the Southampton Oceanography Centre.

Autosub **(right)**

The vehicle is about 23 ft (7 m) long and 3 ft (0.9 m) in diameter and weighs about 3,100 lb (1,406 kg) in air. Payload volume is over 35.3 cubic feet (1 cubic meter). Its depth capability is reported to be over 6,500 feet (1,961 m).

Recently, additional systems have been added to *Autosub* including an altimeter, CTD, acoustic Doppler current profiler, and fluorometer. This still leaves over 300 lb (136 kg) of payload capability in the vehicle for additional mission packages. Chelsea Instruments will manufacture and market the AUV around the world.

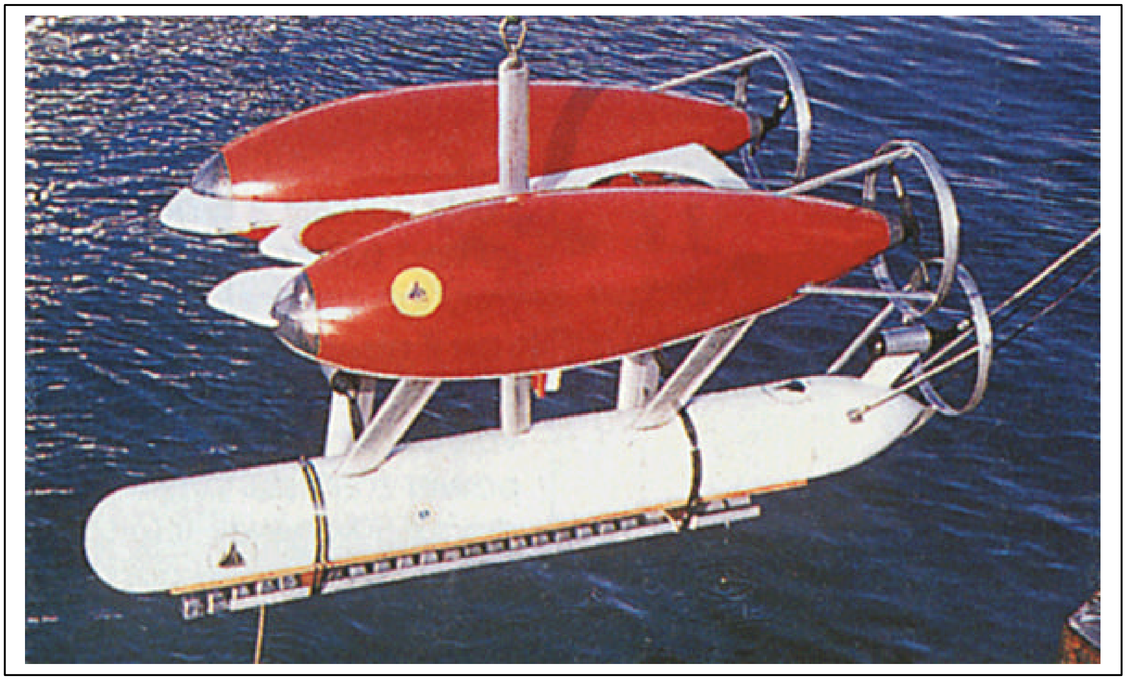
ABE

The Autonomous Benthic Explorer (*ABE*), funded by the National Science Foundation at the cost of about $1 million, does not resemble any conventional torpedo-shaped AUV with its unique three-body shape. Unlike other AUVs optimized for speed and range, ABE is optimized for maneuvering in tight places close to complex bottom topography. The three-body shape allows reasonably efficient forward travel and high stability (with the flotation in the upper two pods) in roll and pitch. *ABE* is designed to travel slowly–about 1 kt (1.9 km/hr) to conserve power.

The vehicle only needs about 20 watts for control and navigation and a 200 watt peak (optimized for 100 watts) for propulsion. The total energy capacity of the batteries is 1 kWh for lead acid, 2.2 kWh for alkaline or 10 kWh for lithium batteries. The AUV will be used to study vent areas such as those on the Juan de Fuca Ridge.

ABE is also designed to operate from a "dock" near the sea floor where it can stay submerged for weeks at a time. Ultimately, it is planned to leave *ABE* on station for several months at a time to conduct science missions.

The vehicle is 10.2 ft (3.1 m) long (overall), 5.5 ft (1.7 m) wide and 5 ft (1.5 m) high. *ABE* has a displacement of around 1,000 lb (454 kg) and its buoyancy is provided by six 17-in (43-cm) glass spheres with a depth capability of 19,686 feet (6,000 m). Propulsion is provided by two main thrusters aft of the two main buoyancy packs, and two vertical and two lateral thrusters provide vertical or side movement.



Woods Hole Oceanographic Institution's (WHOI) *ABE*

The vehicle has a video system consisting of three CCD cameras, two monochrome and one color. A strobe is used to grab a picture, each containing about 1/4 megabyte of data before compression. A recycling time of two seconds is desired for all three cameras, presenting a challenge for both data storage and transfer rate. *ABE* navigates using a high frequency (300 kHz) transponding long-baseline acoustic navigation system. A fluxgate compass provides heading but due to possible magnetic disturbances in the area, is checked and corrected using information from the acoustic positioning system.

The vehicle utilizes a distributed control system with nodes communicating serially. Each node contains a low-power single chip microcomputer (68HC11) with some nodes also containing transputers.

Cryrobot & Hydrobot

NASA and the Jet Propulsion Laboratory have developed two AUVs for the mission of finding life in Antarctica's Lake Vostok. The *Cryrobot* AUV will melt its way through 2.5 miles (4 km) of ice and then release the second AUV *Hydrobot*. The *Hydrobot* will then explore the lake searching for life. Scientists are considering sending the two AUVs to Jupiter's moon Europa.

Military AUVs

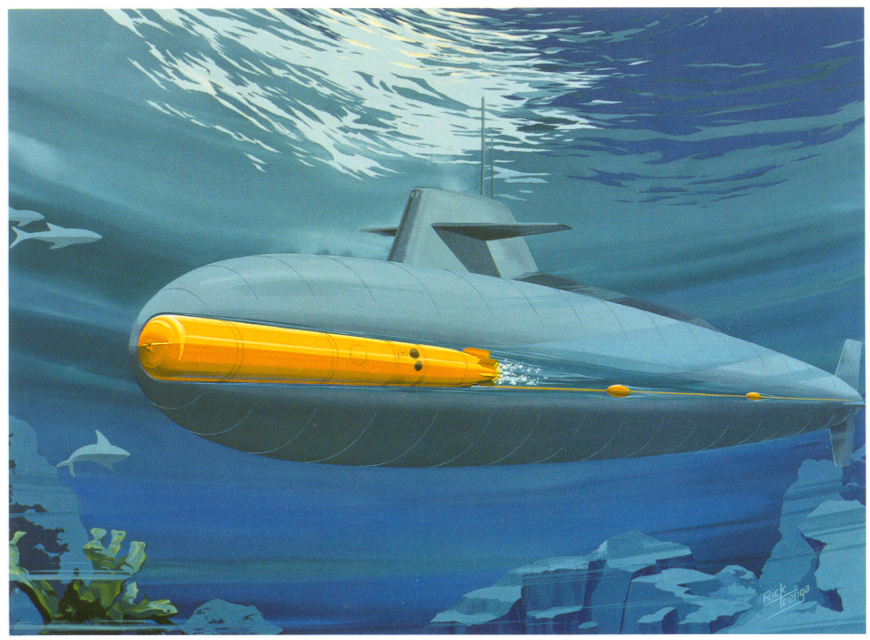
DARPA AUVs

The Defense Advanced Research Projects Agency (DARPA), responsible for high-risk, high-technology programs, funded Draper Labs to design and build advanced AUVs that could be used to demonstrate to the Navy specific military missions such as Mine Reconnaissance and Search.

US Defense Advanced Research Projects Agency's (DARPA) AUVs

Each vehicle is just over 35 ft (10.7 m) long and 3.7 ft (1.1 m) in diameter. Utilizing silver-zinc batteries, the vehicles are capable of an endurance of 24 hours at 10 knots (18.5 km/hr). Maximum depth capability is 1,500 ft (457 m). The vehicles have recently been transferred to the Naval Oceanographic Command in Bay St. Louis, Mississippi, where they will be used for oceanographic applications.

Mk 30 Mod 1



The *Mk 30* is a self-propelled under-water vehicle (target) capable of simulating the dynamic, acoustic and magnetic characteristics of a submarine. These vehicles are used because opera-tional submarines are not always available as targets for Navy exercises and safety is always a concern. ASW vessels and aircraft can demonstrate target detection and classification, trailing, and acoustic homing torpedo attack missions. *The Mk 30* can run 3-dimensional run patterns autonomously. They can be launched from 21-in (53-cm) diameter torpedo tubes and launchers. Once in the water, *the Mk 30* unreels a 390-ft (119-m) towed array used to simulate submarine characteristics.

The *Mk 30* is composed of six separate hull sections fabricated of aluminum castings or forgings. The hull is 21 in (53 cm) in diameter and 20.4 ft (6.2 m) long. The vehicle weighs 2,700 lb (1,224 kg) in air. Propulsion is provided by a 107 hp, dc, series-wound motor (counter-rotating armature/field type) connected through two concentric drive shafts to counter-rotating propellers. Guidance and navigation (dead reckoning) is provided by a Bendix digital navigational computer that accepts commands from the acoustic link.

The *Mk 30* can travel at speeds of 7-30 knots (13-56 km/hr) at depths from 25-2,000 ft (8-610 m). It has endurance on its silver-zinc batteries of up to 4 hours depending upon speed. Commands to the vehicle are transmitted by a standard Navy underwater telephone (AN/UQC-1 or AN/WQC-2). Up to 10 discrete commands can be transmitted via a single sideband suppressed carrier acoustic signal.

***MK 30 Mod 1* ASW Mobile Target**

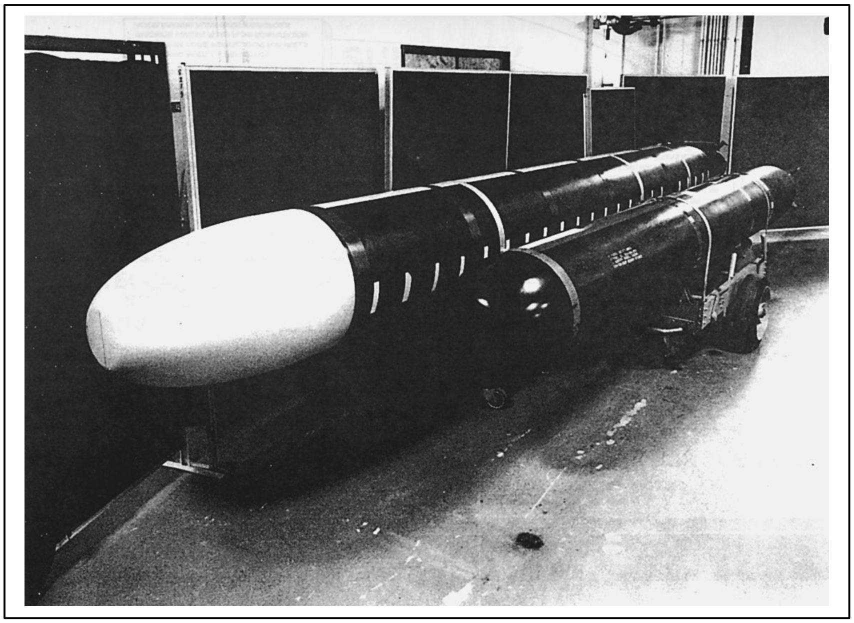
The *Mk 30 Mod 1* is still in use, but is to be replaced by the Mod 2 currently under development by Raytheon for the Navy. The new vehicle is intended to solve reliability, maintainability and logistics problems associated with the Mod 1 system. Mod 2 will utilize the existing infrastructure. After the initial development program, 61 vehicles are planned, some of which may be used for other AUV missions.

Navy's Large-Diameter Vehicle

The Naval Undersea Warfare Center (NUWC) has developed two AUVs–a large diameter and a small diameter vehicle. Of particular interest is the Large-Diameter Vehicle (*LDUUV*). This AUV is being used by ONR to develop and demonstrate key AUV technologies.

The *LLUUV* is nearly 25 ft (7.6 m) long, 2.2 ft (0.7 m) in diameter and is fully autonomous, capable of dives to 650 ft (198 m). It has an endurance of 25 mile (40 km) at speeds of 4-13 knots (7.5-24.2 km/hr). The AUV has a payload capacity of nearly 1,000 lb (454 kg). Propulsion is provided by two axial-field, brushless DC motors driving counter-rotating ducted propellers located on the tail of the vehicle. Control fins are arranged in an "X" configuration. Power is provided by 140 amp-hr silver-zinc batteries providing a 90-VDC bus at 120 volts.

Navigational sensors included an Allied Signal Inc. model RL34 ring laser gyro inertial navigation system, EDO model 3040 Doppler velocity sonar, and a Sensotec Inc. pressure sensor. The INS provides information on attitude, velocity and position.



U.S. Navy's *LDUUV* and *SDUUV* (left)

Heading drift is contained to less than 0.01 deg/hr, INS velocity drift is 1.97 ft/sec (0.6 m/sec) and the corresponding positional accuracy drift is 0.25 miles/hr (0.4 km/hr) without aid from the Doppler.

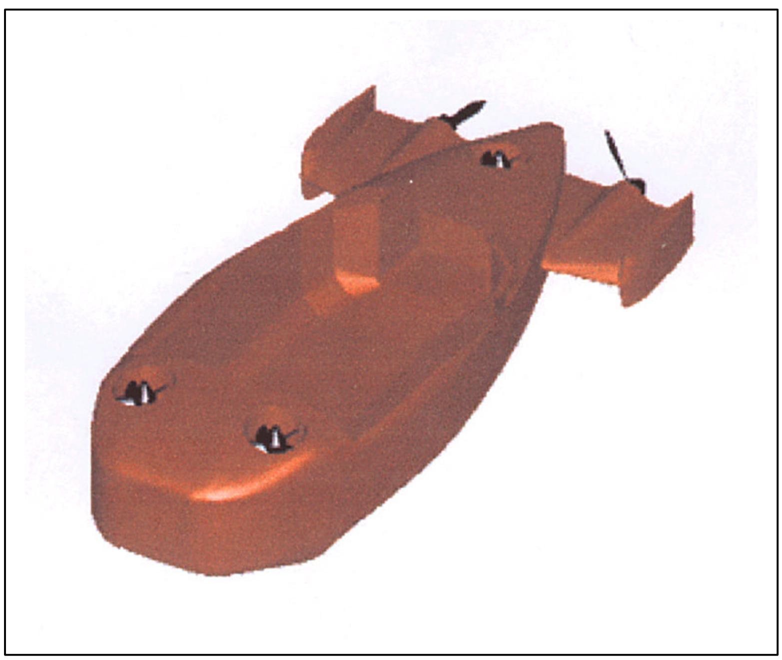
The vehicle contains an acoustic link developed by Woods Hole capable of transmitting data at a burst rate of 31 kbits/s and an aggregate rate of 3.8 kbits/s at a range of about 9800 ft (2,987 m).

The vehicle is commonly fitted with an array of oceanographic and survey equipment for technology demonstrations and evaluations.

Cetus

Cetus is a version of *Odyssey*, designed for Lockheed Martin for mine countermeasures. This small AUV resembles a hydro-dynamic ROV, as do many of the modern designs. For an AUV to be useful in performing tasks such as inspection, identification, recovery, mine disposal, etc., it must be able to hover and hold position in the water column.

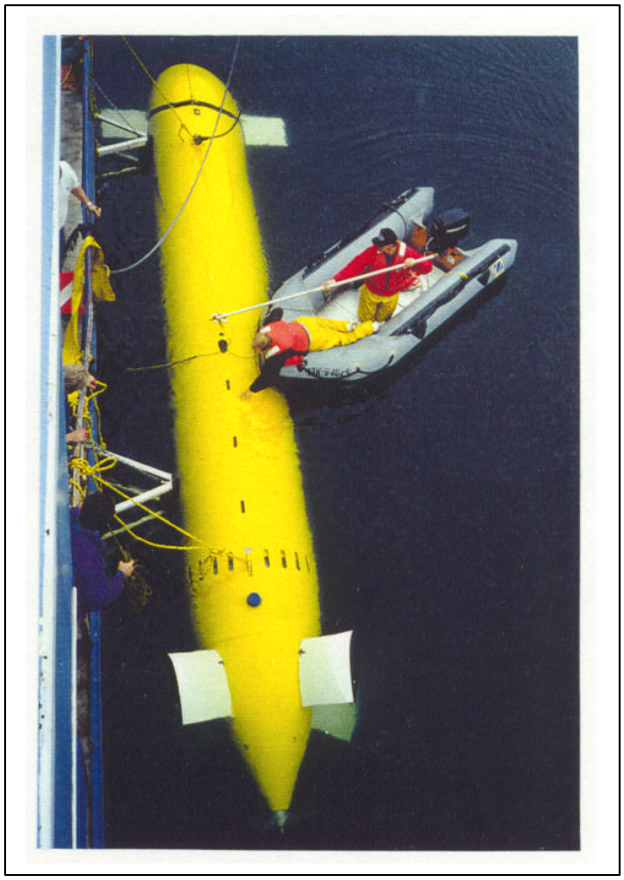
Lockheed Martin's *CETUS* (right)



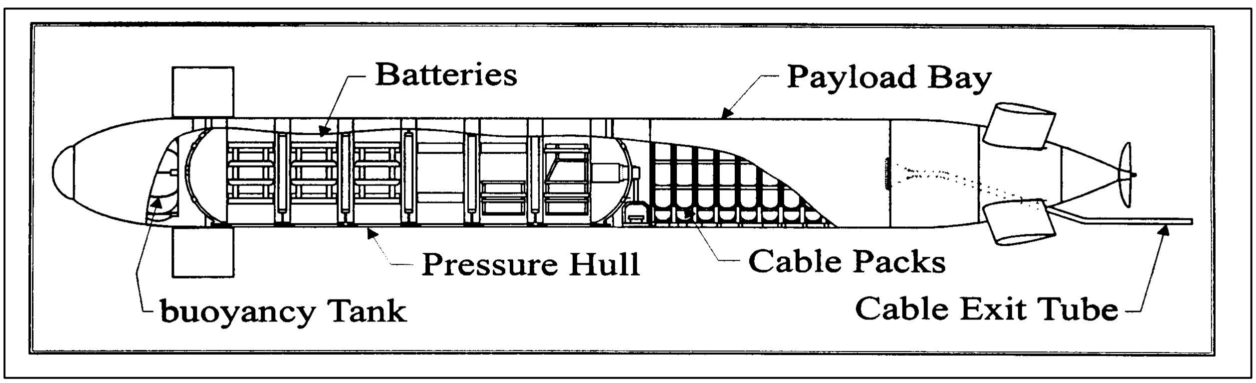
Cetus is 6 ft (1.8 m) long, 2.6 ft (0.8 m) wide and 1.6 ft (0.5 m) high and weighs about 330 lb (150 kg) in air with full payload. The AUV is rated to 650 ft (198 m) with aluminum pressure vessels and 13,000 ft (3,962 m) with titanium pressure vessels. The vehicle is configured with two main thrusters aft and three vertical thrusters for hovering. *Cetus* is currently powered by lead acid batteries and has a maximum speed of 5 knots (9.3 km/hr) and range of 25 miles (40 km). The hull is fabricated from rotary molded high impact plastic. *Cetus*, although looking very different from *Odyssey*, uses essentially the same components internally.

Theseus

International Submarine Engineering (ISE) developed the large AUV *Theseus* under contract to the Canadian Defence Research Establishment Pacific (DREP). The AUV began development in 1992, made its first dives in 1994 and became operational in 1996. The earlier built *ARCS* AUV, which is an approximate 1/2-scale version of *Theseus*, was used to test prototype systems and vehicle hydrodynamics. The vehicle has demonstrated its ability to autonomously lay fiber optic cable–over 19 miles (30 km) of cable have been laid to date. The longest single cable laid was 7.5 miles (12 km) long. Additionally, *Theseus* has made a 3.5-mile (5.7-km) under-ice run and an endurance run of 252 miles (405 km) at a depth of 1,000 ft (305 m).



ISE's *Theseus* AUV (right) and schematic (below)



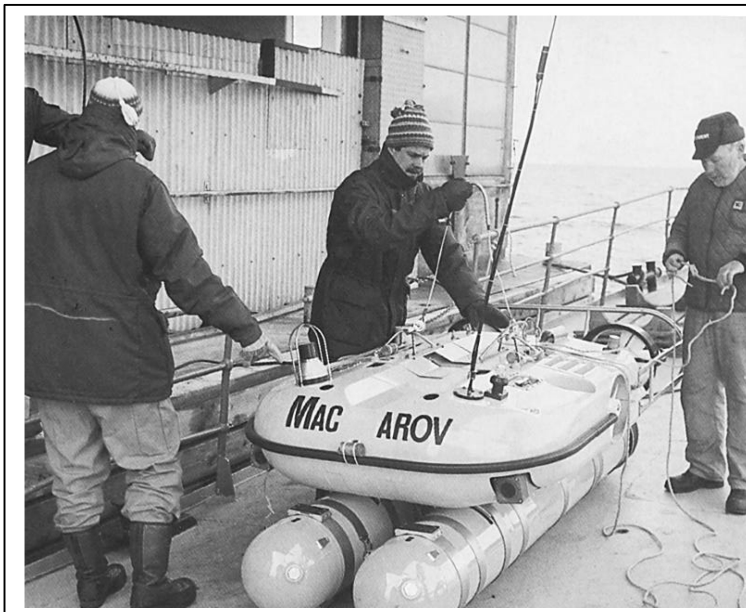
Theseus is 35 ft (10.7 m) long, 4.2 ft (1.3 m) in diameter and weighs 19,000 lb (8,617 kg). Its payload bay is 8 ft (2.4 m) by 3.7 ft (1.1 m) in diameter. It has a cruising speed of 4 knots (7.4 km/hr) and a range of 275 nm (510 km). It can dive to 3,250 ft (991 m) and is propelled by a 67.5-hp Kollmorgen brushless DC motor driving a single propeller. Power is provided by 20 kWh of Ni-Cad batteries or 274 kWh of silver zinc batteries. It uses six electrically powered hydroplanes, two aft of the nose and four diagonally configured fins on the stern.

The hull is fabricated of 1.35-in (3.4 cm) thick 7075 aluminum, consisting of six 24 in (61 cm) long ring-stiffened cylinders with aluminum domes at each end. The pressure hull houses the power source, vehicle electronics and inertial navigation system. The vehicle has GRP free-flooding payload sections forward and aft, which contain sensors, and forward and aft variable ballast tanks–capacity of 550 lb (250 kg) each, 1/2 filled at the start of the dive). For navigation, the AUV uses a Honeywell MAPS inertial navigation unit coupled with an EDO 3050 Doppler sonar. It has a low-frequency Sonatech ACU-206 homing device and a Sonatech STA-013-1 forward-looking obstacle avoidance sonar. Like most of the AUVs currently in operation, it uses a Datasonics acoustic modem for communications with the vehicle.

Mac AROV

Two *Mac AROV* vehicles, based on the SUTEC *TWIN* vehicle design, have been delivered to the Swedish Defense Administration thus far. They are being used to study automatic control and maneuvering and are operated tetherless using battery power. The vehicle is controlled via two bi-directional links; a 4800-baud UHF radio link (470 MHz) or a 20 kHz acoustic telemetry link.

Communication is primarily by an acoustic link that has a range of about 6,500 ft (1,981 m) in shallow waters. Transmission rate is about 10 bits/sec. The radio link, used only at the surface, has a range of 650 ft (198 m). It is used for real time joystick operation and for downloading preplanned routes to the vehicle. Real-time control is used during launch and recovery of the vehicle.



SUTEC's *Mac AROV*

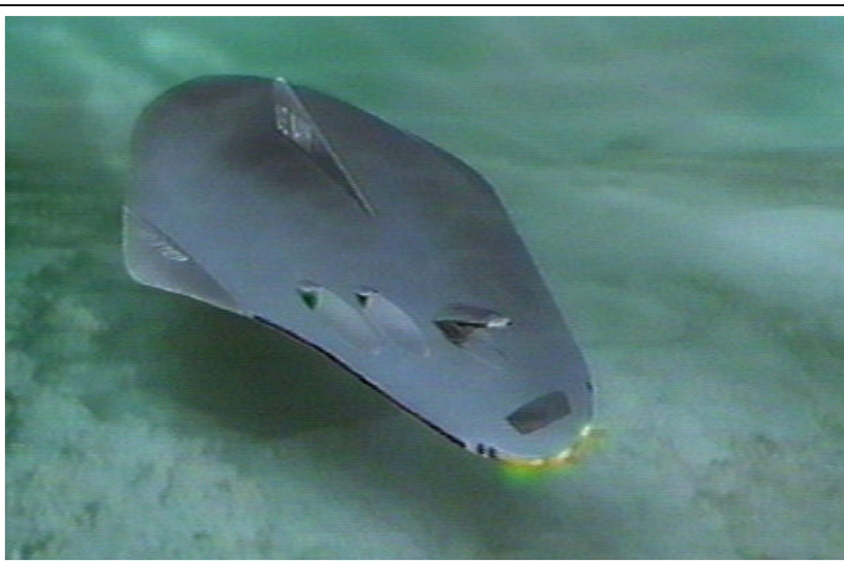
Phoenix

The US Naval Postgraduate School has developed a small AUV called *Phoenix*, a mine countermeasures vehicle, for the purpose of demonstrating mine field mapping or intervention tasks. The vehicle uses the "flat fish" hull design similar to *Martin*.

U.S. Naval Postgraduate Schoo*l's* *Phoenix* (right)

Manta

A futuristic, sleek, Skate-like AUV called *Manta* is being considered by the US Navy's Submarine Technology Program. The vehicle, which would be operated by wire, would be located in a submarine's skin and would be capable of being launched into a minefield, perform reconnaissance or attack an enemy submarine.



***MANTA* AUV Concept**

The US Navy is looking to DARPA to fund up to $100 million in the development of a full-size vehicle that could be operational by 2010. The Navy is interested in embedding up to four vehicles in the submarine's skin for various operations. If the program proceeds further it will probably take on the form of subsystem or technology development programs, including structures, communications, sensors and advanced weapons, which will have to be demonstrated prior to the construction of the *Manta* itself.

MAUVE

Thompson Sintra ASM developed *MAUVE* (Mini Autonomous Underwater VEhicle) to validate at sea a miniaturized, reconfigurable AUV dedicated to multipurpose survey. The AUV was derived from an existing, low-cost training target called *CALAS*, built for the French Navy.

Miniature AUVs

Fetch

On the small, low-cost side of AUVs, Sias Patterson Inc. has introduced *Fetch*, touted as being the world's first commercially available AUV. The vehicle utilizes a two-piece aluminum hull with all stainless steel O-ring seats and fittings. The instrument and motor mount assemblies are machined from polycarbonate for high strength. An antenna and strobe tower extends above the vehicle for at-surface communications and location. The fins are flexible to minimize damage during operation. External RS-422 and battery charging ports allow reprogramming and recharging without disassembly.

The vehicle is 5.7 ft (1.7 m) long and weighs 170 lb (77 kg) in air. Endurance is 4-6 hours with a standard battery or 12-18 hours with a silver-zinc battery. Its range is 10 or 30 nm (18.5 or 55.5 km) depending on battery type used. Fletch’s maximum speed is 9 knots (16.7 km/hr) and its maximum depth is 1,000 ft (305 m).

Sias Patterson's *Fetch*

Fetch is programmed using National Instruments' *LabVIEW®*. The vehicle can act as a node on a TCP/IP network and multiple vehicles can be linked to the network to perform coordinated tasks. Standard sensors include precision depth and temperature sensors, fluxgate compass, GPS receiver, packet modem and transceiver (UHF, spread spectrum or cell phone), 220 kHz scanning marine sonar, pinger, and color video camera.

The vehicle also comes with a RISC computer with 24 Mb RAM, 500 Mb hard drive, frame grabber, restart computer, National Instruments NB-MIO-16 I/O board, nuLogic NuSTEP motor controller, launch/maintenance frame and tool kit. Terrain following software is under development to enhance its capability and a side scan option is also under development.

Navy Mini-AUVs

The Navy has for years been interested in the concept of using multiple mini-AUVs for certain operations. In 1996, the US Naval Undersea Warfare Center (NUWC) released another RFP for a maximum of five AUVs. NUWC was interested in investigating a "UUV Flotilla concept" to conduct rapid, low cost experiments using vehicles in formation to transect/acquire tactically relevant environmental data. The flotilla concept requires small, affordable AUVs, specified by the Navy to be 6.25 to 8.00 in (16 cm to 20 cm) in diameter and no more than 108 in (274 cm) long. Speed would range between 3 to 8 knots (5.6 to 14.8 km/hr) with an endurance of one hour at 6 knots (11 km/hr). Depth capability is 300 ft (91 m).

SEASHUTTLE

The Applied Physics Laboratory at the University of Washington has for years been working in the area of collecting data under ice, specifically the Arctic. In the early 1970s, APL developed an inexpensive, expendable, mobile underwater training target for training sonar operators aboard destroyers. This device was later named the *Mk 38*. In the late 1980s, with ONR funding, the *Mk 38* was augmented with an active guidance system, active homing system and small payload capability. This low-cost AUV was named *SEASHUTTLE* and was launched in 1988.

In 1989 two *SEASHUTTLE*s were fitted with CTDs and precision depth sensors and named the Autonomous Conductivity Temperature Vehicle (*ACTV*). The *ACTV*s made more than 50 successful runs under the ice pack in 1989, 1991 and 1992. A later vehicle was built that stretched a line between two ice holes as far as 3,500 ft (1,067 m) apart. This vehicle was named the Autonomous Line Deployment Vehicle (*ALDV*).

The *SEASHUTTLE* design is based on the concepts of the *Mk 38*, which is no longer in use by the Navy. The vehicle consists of a glass-filled ABS tail section, internal supports, aluminum hull and a dual ceramic ring transducer forming the forward hull section. Two linear actuator motors move the control surfaces and a 1/4 hp permanent magnet motor drives a single 3-bladed propeller. The pressure hull contains two printed circuit boards located above a lithium/sulfur dioxide battery pack (5.4 amp-hr, 30 volts) and has room for an internal payload.

Hermes

The MIT Sea Grant Underwater Vehicles Laboratory also developed a micro AUV called *Hermes*. It is 2.36 ft (0.7 m) long and about 3.5 in (8.9 cm) in diameter. It weighs just less than 10 lb (4.5 kg) and can dive to over 300 ft (91 m). Its speed is 3 knots (5.6 km/hr) with a range of 12 miles (19 km). These types of vehicles can be used for studying the dynamics of underwater chemical plumes, pollution monitoring, hazard assessment, exploration of dangerous and confined spaces, and tracking marine animals.

Gliders

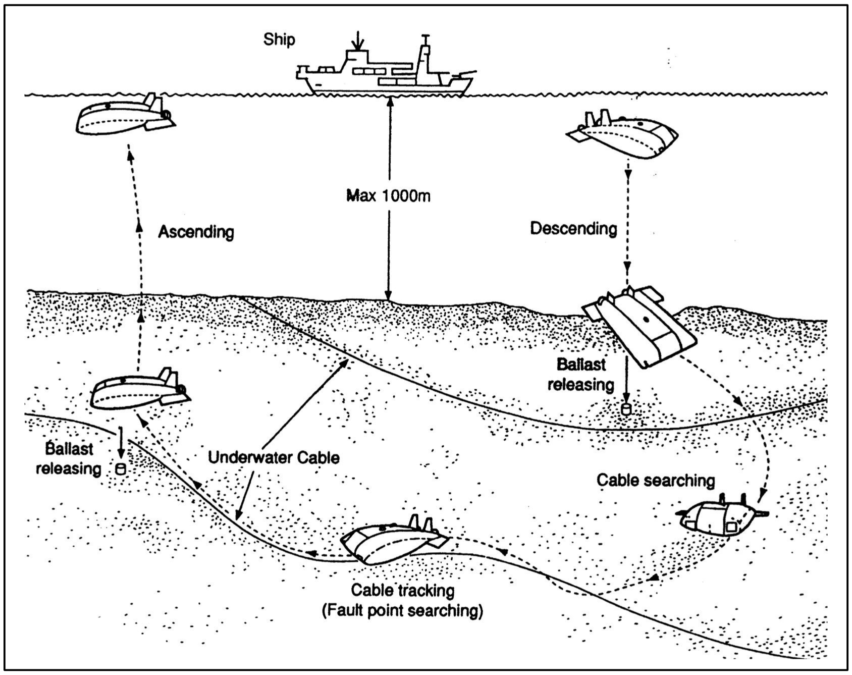
The following four are glider-type AUVs, three built by the Japanese and one by the US. The glider concept has some merit for certain tasks and they can be built at a much lower cost than systems requiring propulsion.

PTEROA 150

In 1986 the *PTEROA* Project was started, funded by the Ministry of Education and Science of Japan. The *PTEROA 150* (see adjoining figure), completed in 1989, was developed as a high performance autonomous glider, designed to cruise over a complex sea floor while taking oceanographic measurements and photographs of the bottom.

The AUV could dive to 6,500 ft (1,981 m) and cruise for one hour at two knots (3.7 km/hr). Four active down-looking sonars were used to determine the shape of the sea floor.

Aqua Explorer 1000



The *Aqua Explorer 1000*, a vehicle that looks similar to the *PTEROA 150*, was developed by the Tokai University. It utilized the gliding capability of the *PTEROA 150*, but was designed specifically to inspect telecommunications cables to 3,300 ft (1,006 m).

Tokai University's *Aqua Explorer* (left)

ALBAC

The Institute of Industrial Science's *ALBAC* is a prototype shuttle AUV designed for water column data collection to about 1,000 ft (305 m). The vehicle moves horizontally without expending much energy from the batteries by moving a trim weight within the body to change its angle. A pair of large NACA 0009 symmetrical wings provides its lift force. The vehicle begins its descent heavy and assumes an angle between 15 and 30 degrees. Once at its destination it drops a weight and begins its ascent.

Institute of Industrial Science's *ALBAC*

Slocum

Doug Webb, of Woods Hole Oceanographic Institution, invented the *Slocum*, a gliding AUV with a very unique automatic cycling thermal engine. It uses liquid glycol to fill an external bladder causing it to float. To dive, a three-way valve is closed allowing the glycol to flow into an internal bladder. The cold temperatures at depth freeze the liquid hydrocarbon into a solid, creating a space that is filled by glycol from the internal bladder. When it's time to ascend, the control valve is closed the other way, and compressed nitrogen from the top of the tank pushes glycol out of a metal bellows into the external bladder causing it to float (surface) again. During the ascent, as the hydrocarbon melts again, it pushes glycol back into the bellows, compressing the nitrogen and making *Slocum* ready for the next dive. Research regarding this unique vehicle is continuing under support from the US National Oceanic & Atmospheric Administration (NOAA) and the Office of Naval Research (ONR).

Towed Systems, Bottom Crawlers, Hybrids and Plows

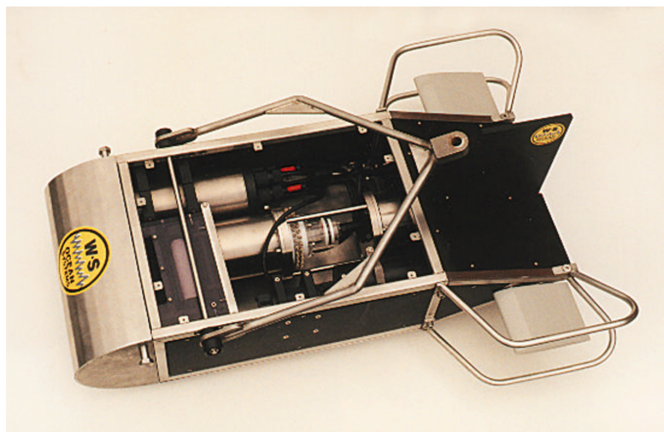
This section captures those "other" vehicles that comprise a very large number of systems used around the world. These include towed vehicles, bottom crawlers, hybrid ROVs and plows.

Towed Systems

This class represents an overwhelming number of systems that have been towed behind ships and boats to perform many different types of work. Towed systems can be broken down into several classes as follows:

Data Collection (Oceanographic) Systems

This class of towed vehicle consists of small vehicles that carry a variety of oceanographic sensors for data collection. Many are designed to undulate through the water column in order to provide profiles (e.g. plankton, etc.). Typical sensors used aboard these vehicles are CTDs, transmissometers, flourometers, nephelometers, bioluminescence and irradiance meters, optical plankton recorders, dissolved oxygen, pH, chlorophyll and others.



W.S. Ocean Systems Ltd.'s *U-TOW*

Survey (Search) Systems

This class ranges in size and weight from very small, shallow water bodies to large full ocean depth systems. These systems are used to survey the sea floor for many purposes including mapping, search and salvage, route survey, pipeline survey, environmental survey, etc. These systems carry a variety of survey sensors including TV cameras, film cameras, digital cameras, laser imaging systems, side scan sonars, swath bathymetry sonars, multibeam sonars, sub-bottom profilers and magnetometers.

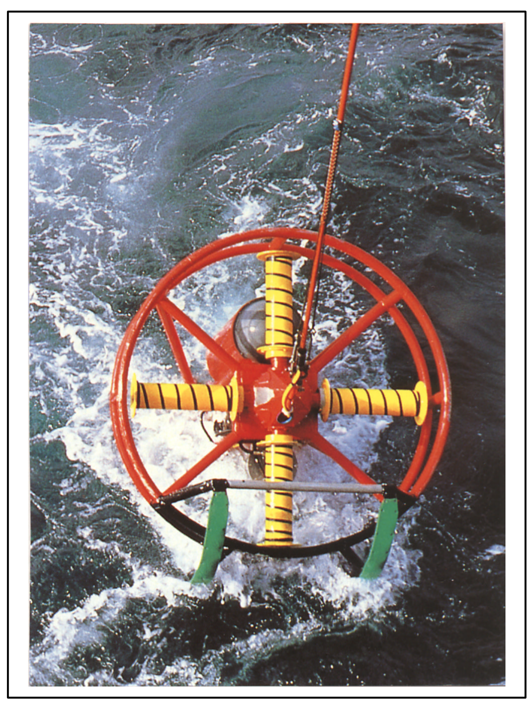
Modern towed systems have incorporated the laser imaging systems such as SAIC's integrated with MacArtney AS' *Focus 1500*.

MacArtney AS' *Focus 1500* (above) Southampton Oceanographic Centre's *Towed Ocean Bottom Instrument (TOBI)* (left)

Cable/Pipeline Location Systems

This class of vehicle is specifically designed to locate cables or pipeline either buried or unburied on the seabed. The vehicles are normally either a conventional towed body, or a sled. The sleds are commonly used in shallow water and are dragged along the seafloor by the surface support craft. Both types carry either a magnetometer or fluxgate gradiometer for locating metallic objects. A very unique design by Seatec, incorporated spinning rotors on the tow body that allow the vehicle to be steered along a pipeline.

Seatec's Towed Vehicle (right)



Towed Vehicles								
Use	Manufacturer	Name	Size LxWxH-m	Depth-m	Type	Wt.-kg	Depressor	Tow Speed
Survey	Univ. of Southampton	TOBI	4.25x1.25x1.5	6000	Neutral	2200	yes - 600 kg	1.5-3 kts
Survey	Woods Hole	ARGO-II	4.6x1.1x1.1	6000	Heavy	2100	no	n/a
Survey	Oceaneering	DOSS	4.0x1.3x1.3	6000	Heavy	1000	no	n/a
Survey		Ocean Expl 6000	4.0x1.2x1.5	6000	Neutral	1225	yes	n/a
Survey	MacArtney A/S	Focus 400	1.5x1.3x1.3	400	Active	200	no	1-5 kts
Survey		Focus 1500	2.6x1.5x1.5	1500	Active	400	no	1-5 kts
Data Collect		Scanfish Mk I	0.75x0.10x0.13	100	Heavy	34	no	2-10 kts
Data Collect		Scanfish Mk II	0.8x1.6x0.14	500	Heavy	50	no	2-10 kts
Survey	Innovatum	Innosled	3.15x1.55x0.85	20	Sled	50	no	n/a
Survey	Okeangeofizika	MAK-1	2.25x1.0x0.95	6000	Neutral	500	yes - 100 kg	6 kts
Cable Locate	Simec SA	Marlin 2	1.37x1.42x0.65	1000	Heavy	220	no	3 kts
Survey	Woods Hole	Medea	2.3x1.0x1.5	6000	Heavy	310	no	1 kt
Data Collect	Guildline Instruments	Batfish II	1.3x1.25x0.9	400-1000	Active Wing	85	no	3-12 kts
Data Collect	Chelsea Instruments	Nv-Shuttle	2.13x0.5x0.58	150	Undulating	73	no	5-15 kts
Data Collect		Seasoar Mk II	2.0x1.6x0.98	500	Undulating	150	no	4-12 kts
Survey	ECA Societe	SAR	5.0x1.0x1.0	6000	Neutral	2500	yes	1 m/s
Video	JW Fischers	TOV-1	0.6x0.17x0.17	76	Heavy	15	no	2-4 kts
Data Collect	WS Ocean Systems	U-Tow	1.2x0.81x0.48	200	Heavy/	100	no	4-20 kts
					Undulating			

Modern Towed Vehicles

Crawlers						
Manufacturer	Name	Size LxWxH-m	Depth-m	Payload (kg)	Wt.-kg	Burial Depth-m
Simec SA	Castor 1	7.0x2.45x2.5	50	5000	12,000	1.2
	Castor 2	8.0x2.45x2.5	1000	5000	12,000	2.2
Soil Machine Dynamics	Eureka	11.0x4.0x4.0	1500	3000	19700	2.2
	Seabed Tractor	6.0x4.9x4.0	1400	2000	11500	1
Perry Tritech	Gator	5.5x4.6	50	n/a	9000	2.2
Travocean	Koura 1	5.3x2.15x2.0	200	n/a	3400	n/a
	Koura 2	5.7x2.2x2.0	200	n/a	5500	n/a
Hydrovision Ltd	Navtrax	1.36x1.1x1.1	1000	400	780	n/a
Subtec STBS Ltd	Pelican	4.7x2.8x2.2	n/a	n/a	8500	3
	Toucan	9.25x2.25x2.2	40	n/a	14700	2.1
Technomare Indust. SpA	Piovra	5.2x4.7x3.3	1500	n/a	13000	n/a
	TM 402C	8.5x7.5x4.0	200	n/a	28000	n/a
Slingsby Engrg. Ltd	ROV 128	4.0x4.04x2.15	2000	50	7300	n/a
	Scarab III	4.5x4.2x2.45	2000	50	9000	n/a
Pirelli Jacobson	Sea Crawler	5.5x5.64x2.43	50	4000	8000	2.5
Coflexip Stena Offshore	TM 9	13.5x5.0x9.2	300	n/a	85000	2.5
Boskalis Offhore BV	Tramrod 200	13.4x4.5x4.1	300	n/a	12000	n/a
	Tramrod 250	5.9x4.2x4.0	800	n/a	38000	n/a

Modern Bottom Crawlers

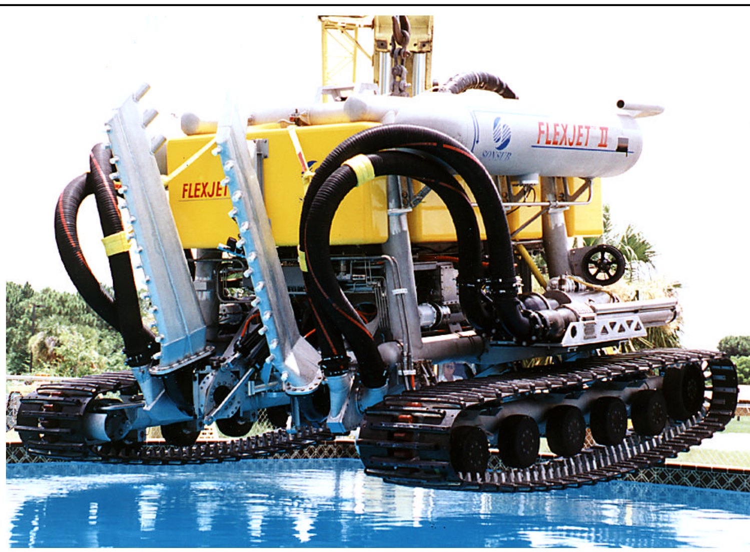
Bottom Crawlers

This class of vehicle is most commonly a tracked vehicle. In some cases an Archimedes screw has been used instead of tracks. The primary use of tracked vehicles has been for cable laying and burial. Cable burial vehicles carry one of four tools for burying purposes; water jets, chain trencher, wheel trencher or plow, which are normally changed out depending upon soil conditions. Some systems can be operated remotely or from a diver station onboard the crawler. Other uses for crawlers are sediment preparation, pipeline trenching and dredging operations.

Perry Tritech's *Gator* (right)

Hybrid Vehicles

There are some vehicles that don't fall into any one class and are in fact, multiple types of vehicles combined or special purpose designs. An example of a hybrid system is Perry Tritech's *Flexjet* system, which is essentially a *Triton* ROV with a tracked vehicle capability. The system has the capability of flying via its thrusters in a neutrally buoyant state or becoming heavy and crawling on the seabed. The system is fitted with a jetting tool for cable or flexible pipe burial. Although the vehicle requires 100 hp to operate normally, an additional 400 hp is provided through the umbilical to power the huge jetting tool for a total power requirement of 500 hp.



Perry Tritech's *Flexjet II*

Two examples of purpose-built systems are the *GRAB*, which was used to recover bullion from a sunken ship and the *Scimitar*, which was used to clean the legs of a fixed platform. Both vehicles were integrated with a standard Perry Tritech control system and utilized *Triton* TMSs.

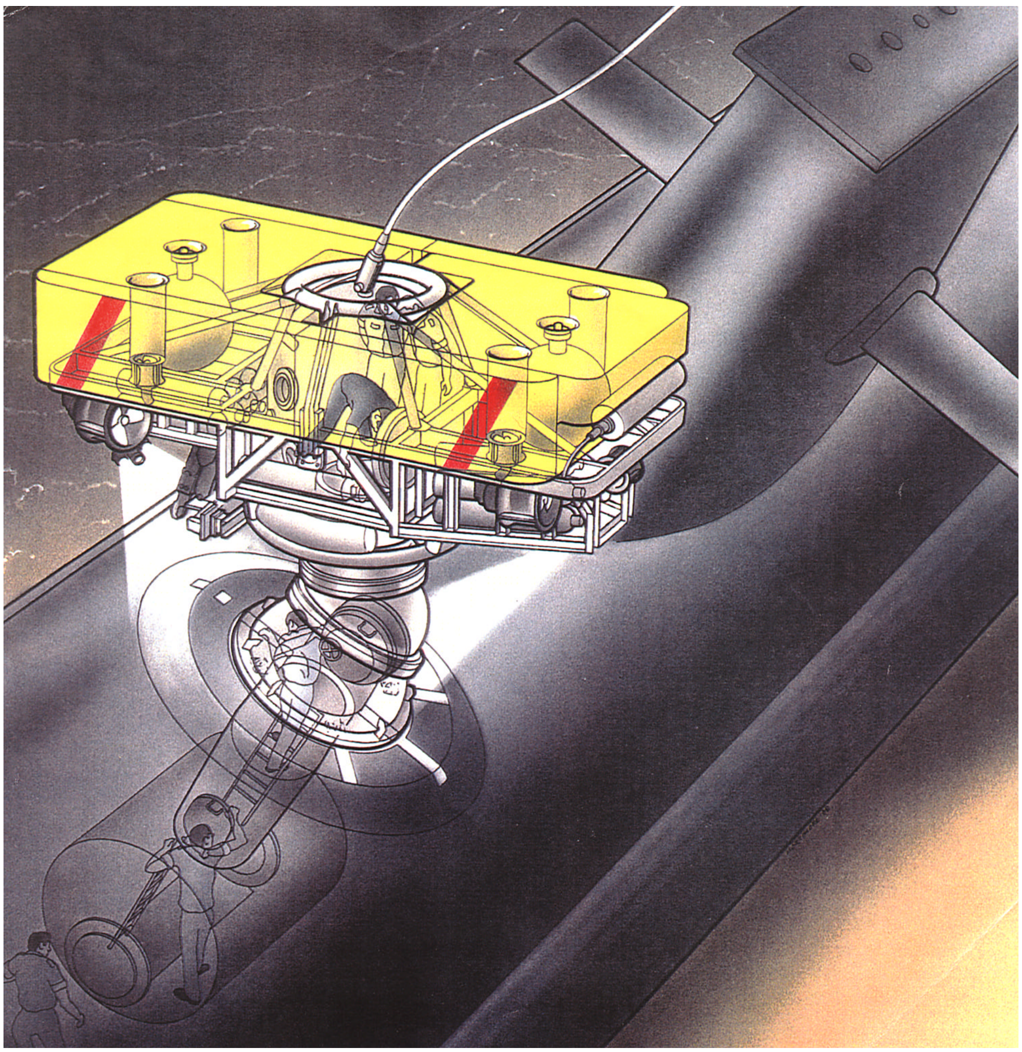
Perry Tritech's *GRAB*

Dawson Offshore/Perry Tritech *Scimitar*

Hybrid ROVs							
Manufacturer	**Name**	**Size LxWxH-m**	**Depth-m**	**Power-hp**	**Wt.-kg**	**Payload-kg**	**Thru Frame**
Hitec Marine	ROP	12.0x1.5x1.5	n/a	n/a	1100	n/a	n/a
SMD	Nereus	3.7x3.1x2.4	2000	240	8200	700	n/a
Perry Tritech	Flexjet II	4.8x4.2x3.8	500	100	12000	400	n/a
Alcatel Kabel Norge	Capjet 500	7.0x4.5x2.5	500	200	11000	400	n/a

Modern Hybrid ROVs

Another very unique approach to a hybrid system involved the submarine rescue system built by Hard Suits Inc. for the Royal Australian Navy. The system, called *REMORA*, is a hybrid ROV and diving bell. The system is flown like an ROV by two pilots aboard ship, but carries a bell attendant inside for making the personnel transfer from the sub to the bell.

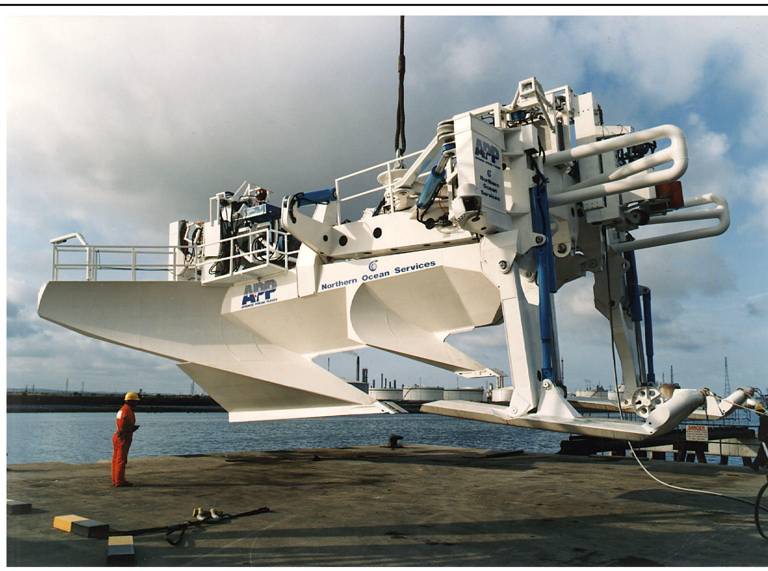


Hard Suits, Inc.'s *REMORA*

Plows

Plows represent another large class of vehicles that have, over the years, become very sophisticated. Plows come in all sizes and configurations, weighing up to 80 tons (81,280 kg), resisting tow forces to 250 tons (254,000 kg) and capable of shallow water work to depths of 4,921 ft (1,500 m). There are as many different plow designs as there are different soil conditions around the world. The figure below of one of Soil Machine Dynamics (SMD) Ltd.'s line of ploughs illustrates the size of such systems and the table on the next page shows the differences and potential burial capabilities of various ploughs.

The primary cause of damage to telecommunication cables is fishing. Deepwater fishing to 6,562 ft (2,000 m) is conducted, therefor, burial just beyond that depth may be desirable or required in the future. Some plows combine a plowshare and water jetting capability. The primary tools used for digging trenches with plows are the share or the disc. Not all plows are used to dig trenches; some specialty plows are built just as back-fill systems for filling in trenches dug by other plows.



Soil Machine Dynamics Ltd. *Plough*

A table showing many of the modern plow systems, or ploughs, based on your spelling preference, is provided on the following page.

Ploughs						
Manufacturer	Name	Size LxWxH-m	Depth-m	Pull-tons	Wt.-kg	Burial Depth -meters
SMD	3M Plough	9.0x4.6x4.0	1500	50	18000	3
	APP/PL 2	18.0x12.0x9.0	400	300	140000	2
	Back Fill Plough	14.0x13.0x4.0	400	300	85000	n/a
	Lt. Weight Cable Plough	9.0x4.6x4.0	500	50	9000	1.1
	Modular Plough	12.0x4.5x6.0	1000	100	27000	1.4
	Multipass Pipe Plough	19.0x10.0x5.5	500	350	100000	1.8
	Sea Plough VI	10.5x6.0x4.0	1000	80	25000	1.2
	Standard Cable Plough	9.0x4.6x4.0	1500	50	14000	1.1
	Surveyor	6.0x3.0x4.0	1500	40	4200	n/a
Simec SA	Elise III	8.0x2.9x2.95	1500	n/a	17000	1.1
Smit Land & Marine Eng.	PBP4	21.0x10.0x7.8	200	n/a	95000	1.8
Kvaerner RJ Brown	Post Trenching Plough	28.0x8.0	150	400	110000	1.8
ECA Societe	Sea Plough	8.5x3.0x2.95	1500	81	n/a	1.1

Modern Plow Systems

CHAPTER 2. WHAT CAN THEY DO?

INTRODUCTION

In Chapter 1, the history of the ROV and the many classes of the systems were discussed. In Chapter 2, this discussion will be carried further into the actual capabilities of modern systems and what they are doing in many areas. The first section will provide a quick Task Summary for state-of-the-art vehicles. This is followed by a more in depth discussion of Commercial-Offshore Energy, Military Missions, Academic/Scientific Applications, and Other Applications, which includes the ever-increasing area of Inland Operations.

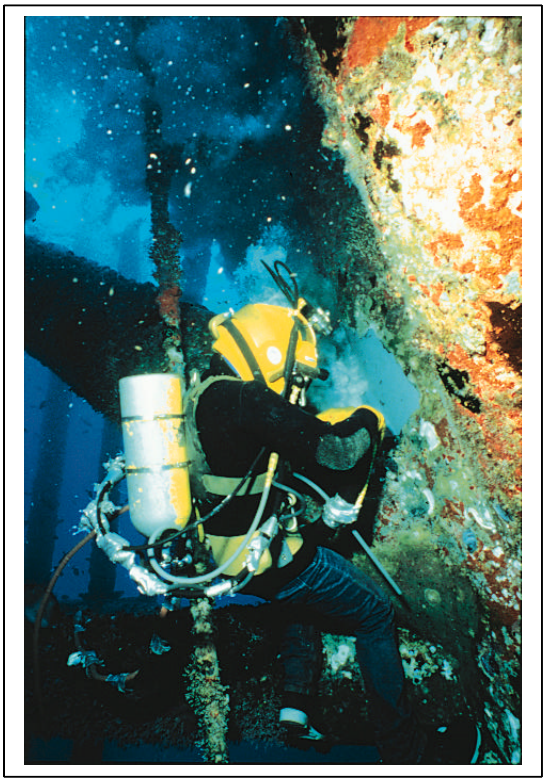
TASK SUMMARY

ROVs

The majority of ROVs in use are working in the offshore oil and gas industry, however they are becoming more common and relied upon for inland and scientific applications every year. The following are some of the common uses for ROVs offshore (inshore applications will be discussed separately):

Diver Observation

In the early days the primary use of ROVs was to observe divers working at dangerous depths and to perform a safety and quality control function. Experts on the surface could direct the diver in his normal duties as well as emergency situations.

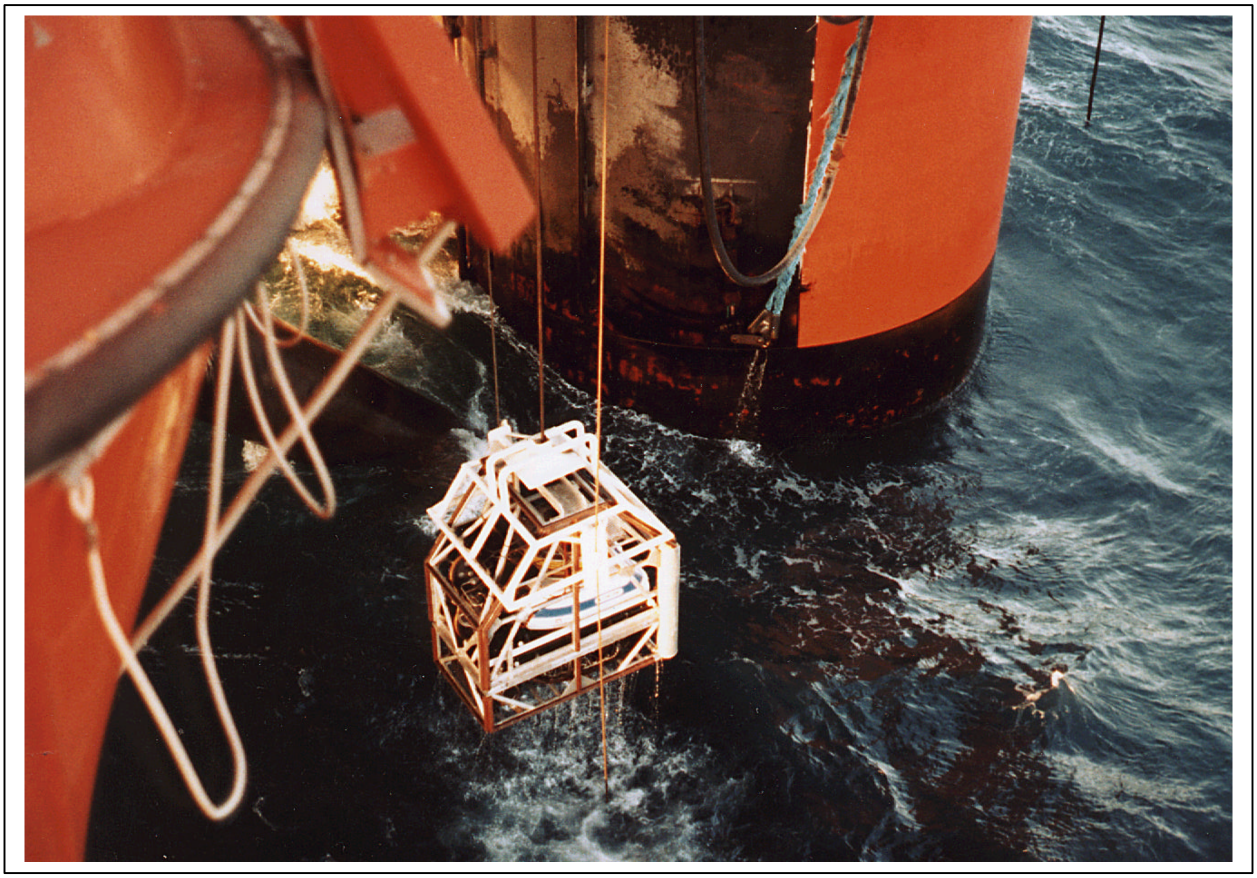


Ceanic diver observed by ROV (right)

Platform Inspection

Regulations require that offshore oil and gas platforms be inspected to look for damage and to determine the extent of marine fouling. Offshore platforms become heavily loaded structurally when the drag increases on the structure due to its increased cross section from extreme fouling. Another task is to check the platforms corrosion prevention systems (cathodic protection).

In addition to general inspections of this type, very detailed inspections are also frequently required. These inspections include looking at critical welds at platform nodes (joints), where cracking can begin to occur, using non-destructive testing (NDT) techniques. If cracks are detected, then repairs must be initiated.



ROV/cage launched from platform

Pipeline Inspection

ROV systems began to be accepted for offshore work after demonstrating their ability to effectively and quickly perform pipeline inspections. The vehicles would often perform visual inspections looking for leaks, unburied pipelines or spans of unsupported pipeline. In other cases the ROV would carry a sophisticated suite of tracking and inspection sensors for performing a variety of tasks. The vehicles were also required to hold position in moderate currents and had to be capable of "live-boating" (i.e. with ship underway), which greatly reduced the time to perform an inspection.

Slingsby Engineering's *Solo* Inspection and Maintenance ROV
(*Solo* now operated by Stolt Comex Seaway A/S)

Surveys

Pipeline inspection evolved into even more work for the ROV through site and route surveys. Prior to installation of a platform, an ROV would perform a detailed search and survey of the area. It would then perform route surveys from the shore to the platform to pick the best installation routes for pipeline and cables. Here the vehicles were required to carry very accurate acoustic tracking systems or work within long baseline acoustic networks so that the position of the ROV was accurately known.

Drilling Support

The most common requirement for ROVs, by a wide margin, is drilling support due to the inherent danger of operating close to this activity as well as the water depths involved today. Here ROVs are required to have very dexterous manipulators for performing complex tasks. Two manipulators are often required, one as a grabber and the other as an extension of the operator at the surface. In addition, these vehicles sometimes require operation in high currents and may have to carry large payloads. The drilling support ROV has evolved from the "hard wired" systems of the 1970s to the fiber optically controlled systems of today. Some vehicles have up to 10 channels dedicated to video cameras alone. This topic will be discussed in more detail later in this chapter.

Construction Support

A natural addition to drilling support capabilities is construction support. This work involves structural repair and installation tasks. These tasks require different capabilities such as cutting, cable attachment, etc., but still require the same manipulator dexterity as drilling support.

Debris Removal

Since ROVs were commonly found around platforms during construction projects, they began to be used to recover debris dropped or left around platforms that were to be removed. The ROVs would attach recovery cables and other lifting devices to the debris.

Call Out Work

A great deal of general offshore work is available for systems not permanently assigned to platforms or drill ships. These systems must be mobilized quickly and be ready to work once on site. Generally, these ROVs are required to perform simple tasks such as observation or AX ring change-outs and cable cutting or attachment. Work can last for one day or for several. Once the work is completed, the system is usually demobilized immediately.

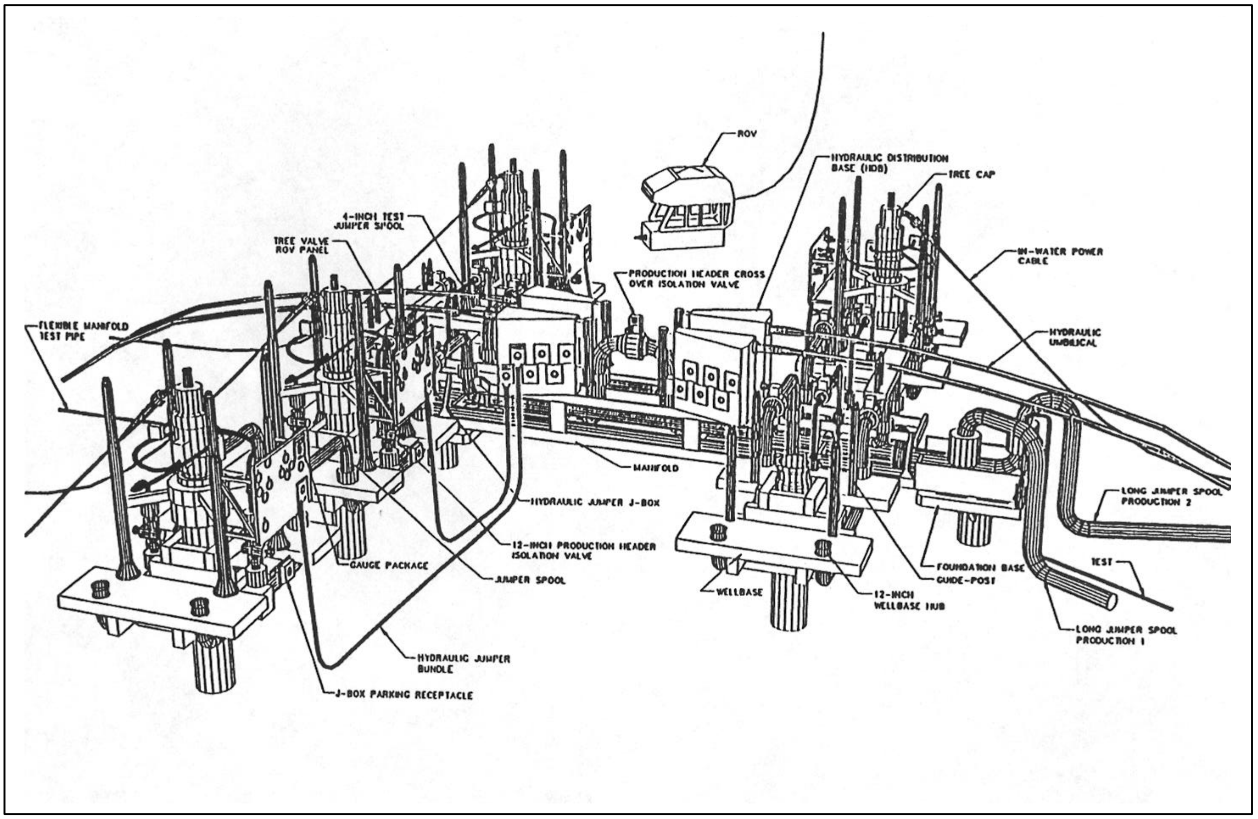
Platform Cleaning

Probably the most sophisticated task asked of ROVs in the 1980s was platform cleaning using brushes, water jets and other abrasive devices. This task was not easy to perform as the ROV would have to attach itself with suction cups or grabbers to an already heavily fouled leg, then initiate some cleaning effort that usually produced a significant reaction force on the ROV, attempting to break it away from its attachment point. This era also saw the first 100-hp systems capable of carrying high pressure water jets to the site for blasting away marine growth.

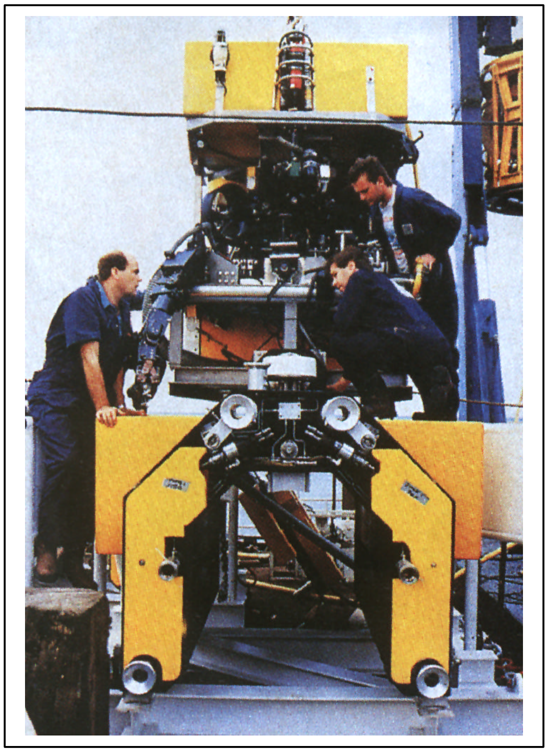
Perry Tritech's *Triton with MOC*-1 Platform Cleaning System (right)

Subsea Installations

As vehicles became more powerful and capable of performing complex tasks, they soon began to support the construction, operation, inspection, maintenance and repair of subsea installations, especially those in deepwater. Today, the ultra-deep water production system most widely used is the subsea completion and is the fastest growing market for ROV use. This technique is the lowest cost approach to deepwater production. It does however, require extensive intervention from ROVs. Because of this the modern ROV giants such as the *Triton XL 250, MRV* and *Hercules* systems have evolved. Some of these vehicles carry as much as 250 hp for high-thrust and heavy work capability. Through-frame lift capability can be as much as five tons or more. It is now apparent that ROVs will be capable of performing this work to depths exceeding 9,843 ft (3,000 m). In at least one case, a ROV was permanently installed on rails on a subsea installation and was used to maintain the manifold.



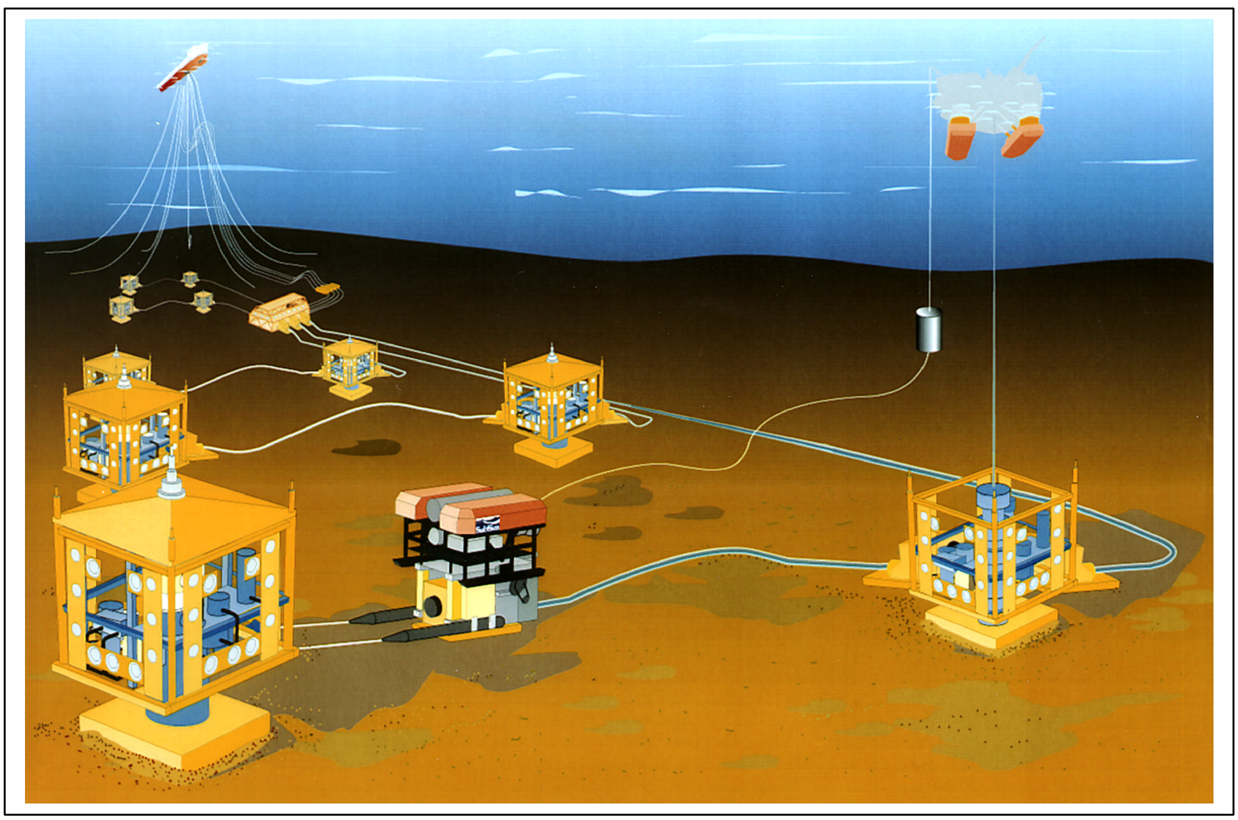
AMOCO's *Liuhua* Subsea Manifold System
(Courtesy of AMOCO)



With the advent of these large and powerful ROVs came the development of Diverless Flowline Connection Systems (DFCS) such as Sonsub's, which was developed for the Amoco Liuhau 11-1 field for 13.5-in (34-cm) and 6-in (15-cm) flexible flowline tie-in operations.

Sonsub International's Diverless Flowline Connection System (DFCS) (left)

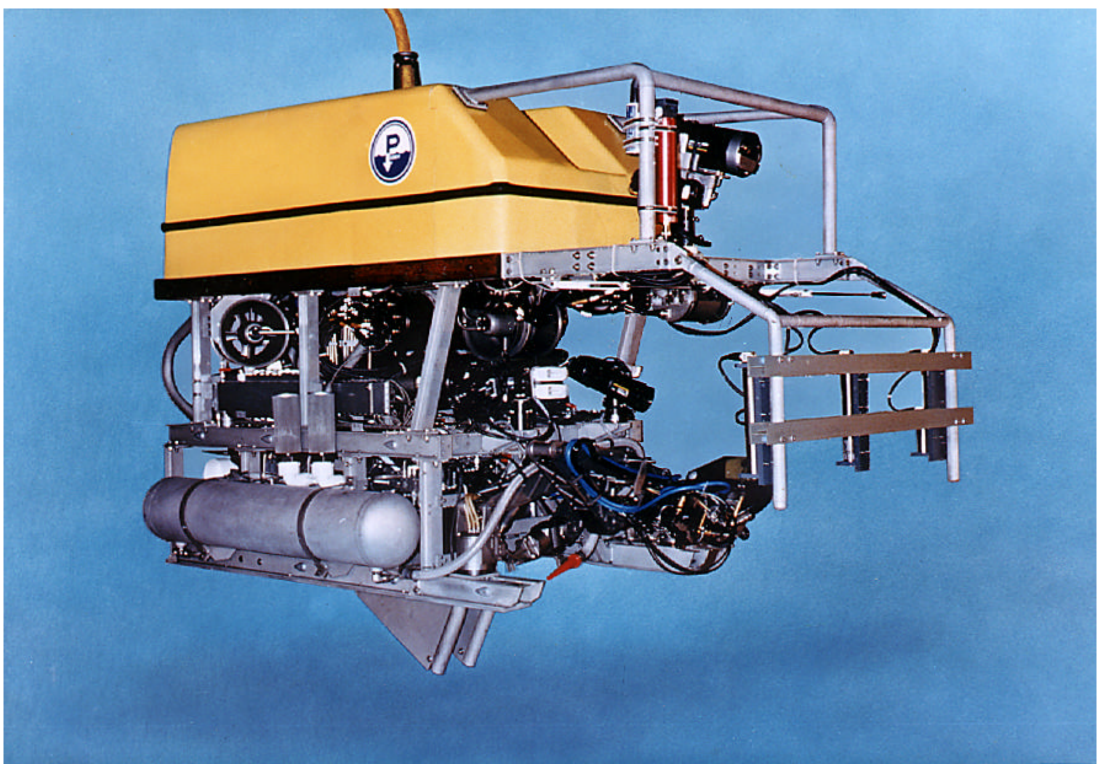
ROV performing subsea tie-in work (below) (Courtesy of Subsea Offshore)



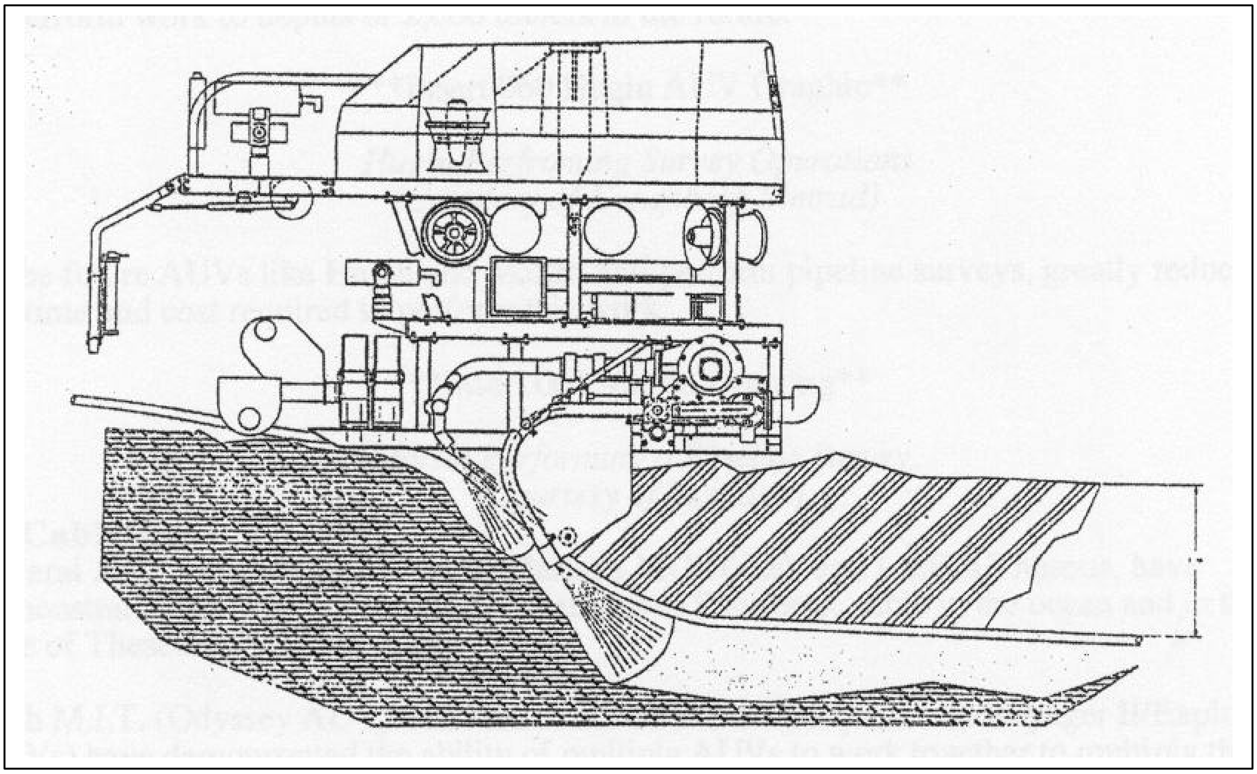
Telecommunications Support – Inspection, Burial or Repair

Over the years, ROVs began to be used for small pipe and cable trenching and burial tasks in soft soils. The heavy seabed plow is still the most effective way to trench and bury cables, however, there are several applications suited to the free-swimming ROV or small ROV tractors. Specifically, these systems can be used for burying exposed lengths of cable after repairs have been made. Jetting techniques can be used where the seabed is soft. More recently, relatively small cable trenching and burial systems have been built that are being used for shore end installations of telecommunication cables. These ROVs are capable of bringing the cables laid by large cable ships to shore from depths of less than 984 ft (300 m). The vehicles carry a suite of tools that allow trenches to be jetted or dug in sand or rock to depths of about one meter. These ROVs are essential, as cable ships cannot get into shallow water. Operations are normally conducted from a barge that carries the ROV, cable and support personnel and equipment.

Systems such as Perry Tritech's Advanced Cable Maintenance Vehicle (*ACMV*) are in use around the world. This vehicle has the ability to pick up a cable or flexible flowline and jet a trench, lay the cable and bury it in one operation. For additional information, refer to Chapter 4 – Cable Burial Operations.



Perry Tritech's Advanced Cable Maintenance Vehicle (*ACMV*)



***ACMV* Jetting Illustration**

In much tougher soil or rock conditions the bottom crawling systems such as the Perry Tritech *Gator* or Flexjet, or Subtec *Pelican* systems have increased capability to operate under these conditions.

Object Location and Recovery

There are several sections in this publication that address the techniques used to locate underwater objects, and the wealth of data on tethered ROVs provides a base of information that proves that little is beyond reach in the ocean depths. The following three examples are provided by Oceaneering Technologies Incorporated (OTECH) and provide highlights of, and insight into the complexity of past recovery missions. OTECH has been involved in many recovery operations and has provided long term support under contract to the Supervisor of Salvage of the US Navy, operating vehicles such as the Navy's *CURV III.*

South African Airways Flight 295 Recovery

On November 23, 1987, a South African Airways Boeing 747 airliner crashed into the Indian Ocean 120 miles northeast of Mauritius, the victim of an onboard fire. In worldwide competition, the South African Department of Civil Aviation selected Oceaneering Technologies, Inc. (OTECH) to survey the wreckage and recover selected pieces to aid in the accident investigation.

In September 1988, OTECH mobilized its *Gemini* ROV system aboard *the M/V Stena Workhorse*. OTECH also set up a forward logistics base for the operation in Port Louis, Mauritius, chartering a local vessel for transportation between there and the crash site.

On site, the OTECH crew deployed and calibrated a long baseline, acoustic navigation system around the crash site, coupling it into OTECH's ALLNAV integrated navigation system. After finding the wreckage on a flat sandy bottom in 14,800 ft (4,511 m) of water, OTECH began charting the debris field. On impact, the plane had broken into almost 300 pieces, some weighing tons, scattered over 3 square miles. In dives routinely lasting over 120 hours, *Gemini* produced hundreds of crystal clear photographs of the debris, and, thanks to *Gemini*'s new fiber optic data link, equally high quality video tape recordings of the wreckage.

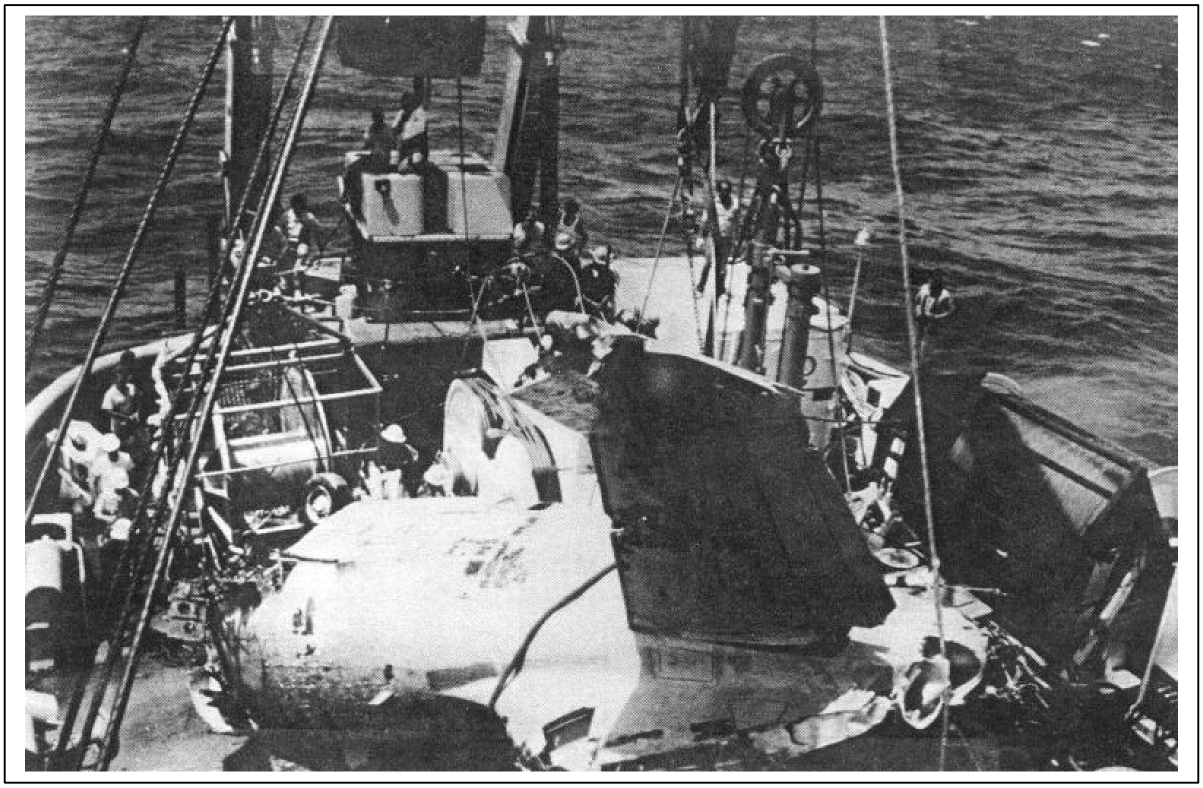
OTECH recovered 10 tons of wreckage for the accident investigators. The vehicle itself brought up pieces as large as 1,000 lb (453 kg). OTECH's heavy-lift, motion compensation system was used for larger pieces. Among the most important was the cockpit voice recorder, located and recovered in February 1989.

S-3B "Viking" Aircraft Recovery

In mid-June, 1990, OTECH deployed aboard the *USS Grasp (ARS-51)*, to recover a US Navy S-3B "Viking" aircraft, which had crashed at sea 200 miles (322 km) southeast of Norfolk, VA. Because the crash site was in the middle of the Gulf Stream, with a water depth of 10,400 ft (3,170 m), OTECH mobilized the heavy-duty *CURV III* ROV system for the recovery. This 80-horsepower ROV has a 20,000-ft (6,096 m) depth capability, and was the only operational vehicle with enough power and service depth to reach the bottom in the 5.5-kt (10.2-km/hr) current there.

Mobilization was not routine. Due to *Grasp's* deck arrangement, a base for *CURV*'s handling system was installed to allow the vehicle to clear stern towing equipment. A motion compensation recovery system also was installed to handle the heavy salvage loads in a seaway. Moreover, OTECH provided a specially designed recovery spool for the ROV, containing the Kevlar lift line for the operation, rigged in a way to ease its use with the vehicle.

Once on site, the operation continued around the clock. After locating the wreckage of the aircraft, OTECH used *CURV* to survey and photo-document the entire debris field. As expected, the aircraft had broken up, shedding its wings and cockpit, but leaving intact the part of primary interest–a 15,000-lb (6,803-kg) section of the fuselage. Not the least of the skills needed that day was the ancient art of rigging–using an ROV! OTECH used *CURV* to rig a bridle through the plane's forked tail hook. Connecting the bridle to the recovery line, *CURV* returned to *Grasp*, streaming the recovery line beneath it as it clawed to the surface. After transferring the bitter end of the line to a deck winch, via the motion compensation system, the fuselage was raised alongside.



SB-3 "Viking" Fuselage on the Deck of the *USS Grasp*

ITAVIA DC-9 Survey & Recovery

In 1980, an Alitalia DC-9 jet airliner crashed in the Mediterranean Sea approximately 80 miles west of Naples, Italy. There was speculation that this airliner might have been the unintentional victim of an errant air-to-air missile. OTECH, teamed as a subcontractor to Wimpol, Ltd., was contracted by an Italian Court in Rome to supply video documentation and recover parts of the DC-9.

The wreckage of the airplane was on the bottom at 11,000 ft (3,353 m), thus, for this task, OTECH deployed its *Magellan-Explorer* search and recovery system aboard the *M/V Valiant Service*. OTECH first performed a broad area search and found that the aircraft had disintegrated in the air, spreading debris over a large area.

OTECH's *Ocean Explorer*, a 19,685-ft (6,000-m) mapping/search dual frequency sidescan sonar, was deployed during the survey phase. Its low frequency mode mapped a 280 square mile (725 square kilometers) area locating the debris field. Once the debris field was located, *the Ocean Explorer 6000* switched to its high frequency/high resolution mode, and mapped 5 areas consisting of 90 square miles (233 square kilometers).

After the survey was completed, OTECH's *Magellan* ROV video-documented the DC-9 wreckage. *Magellan* completed 72 dives with the longest dive lasting 212 hours on the bottom, and provided over 200 hours of videotape and over 1,200 photographs.

Once the video survey was completed, *Magellan* started the recovery phase. *Magellan* completed 85 dives and recovered over 2,500 pieces of wreckage, including the DC-9 Cockpit Voice Recorder.

COMMERCIAL – OFFSHORE ENERGY

Introduction

By far the greatest use of ROVs and associated engineering around the globe is in their application to the oil and gas industry in the exploration and exploitation of hydrocarbons. Since the mid-1970s, ROV technology has aided man in his relentless search for energy beneath the sea.

Time, technology and experience has developed ROV systems from an unreliable visual aid to divers in their formative years to today's highly sophisticated, capable and reliable work class systems routinely undertaking operations in water depths greater than 7,000 ft (2,134 m).

Although regulations vary internationally, generally saturation diving techniques are prohibited in water depths greater than 850 ft (259 m) of water. As a considerable percentage of offshore oil and gas reserves are located in water depths in excess of diver depths, the importance of ROV technology is significant.

Typically, industry categorizes water depth as:

- "Shallow" 0 to 2,000 ft (0 to 610 m)
- "Deep" 2,000 to 5,000 ft (610 to 1,524 m)
- "Ultra Deep" Over 5,000 ft (1,524 m)

Man has adapted several standard means of extracting hydrocarbons in various water depths. From jackup drilling production rigs in very shallow water to subsea completion, tension leg platforms (TLPs) and spars in deep and ultra deep water (see Support Platforms, Chapter 7).

ROV technologies support operations for all of these installations. Primarily, these services are categorized as follows:

- Drilling and completion
- Installation/construction
- Inspection/maintenance and repair
- Other activities

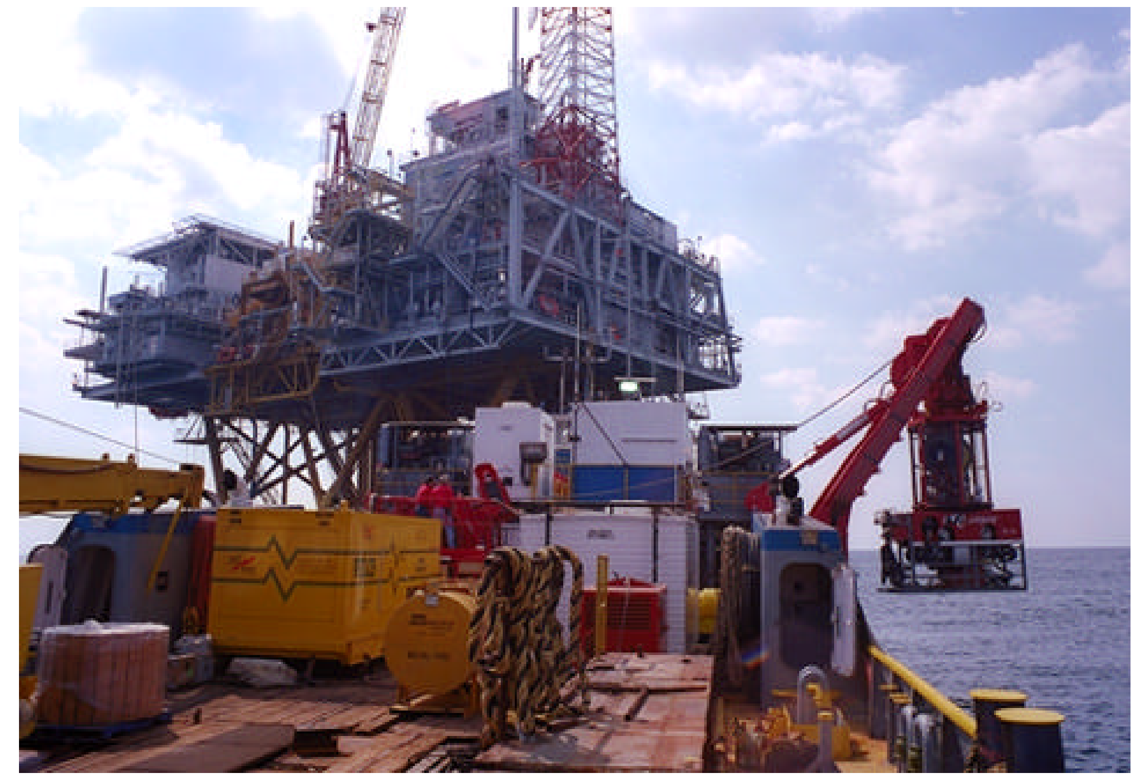
Drilling and Completion

General

Over 60 percent of the world's ROV systems supporting oil and gas exploitation are engaged in drilling support operations. Systems are utilized in water depths as shallow as 100 ft (30 m) on jackup rigs and as deep as 10,000 ft (3,048 m) on semi-submersibles and drillships.

The primary role of ROV systems on drilling support operations is as a visual aid. With the exception of planned activities engaged in during completion operations, all other activities are generally of a contingency nature.

This means that the full range of ROV systems are engaged worldwide to support these activities. Observation ROV systems are typically used in shallow water and when surface trees are utilized. Work class ROV systems are used in deeper water, areas of high current, and when intervention tasks require the use of manipulators, fluid transfer or load bearing capabilities.



Typical offshore ROV installation

Scope of Services

Typical task requirements during exploration and production drilling are as follows.

Exploration	Completion (in addition to Exploration)
• Seabed survey • Anchor survey • Observation during spud in • Monitor bullseye • Monitor cement returns • AX / VX changeout • Connect/disconnect guidewires • Observe landing of BOP stack • Relocate drill string • General visual • Observe drill string inclination • Observe P & A • Recovery of lost items	• Install tree running tool • Pressure test tree and valves • Make up guide funnel to tree • Land tree on wellhead • Lock connector • Make up hot stabs • Run, set and test tubing hanger • Run and install debris cap • Install and connect jumpers

System Configuration

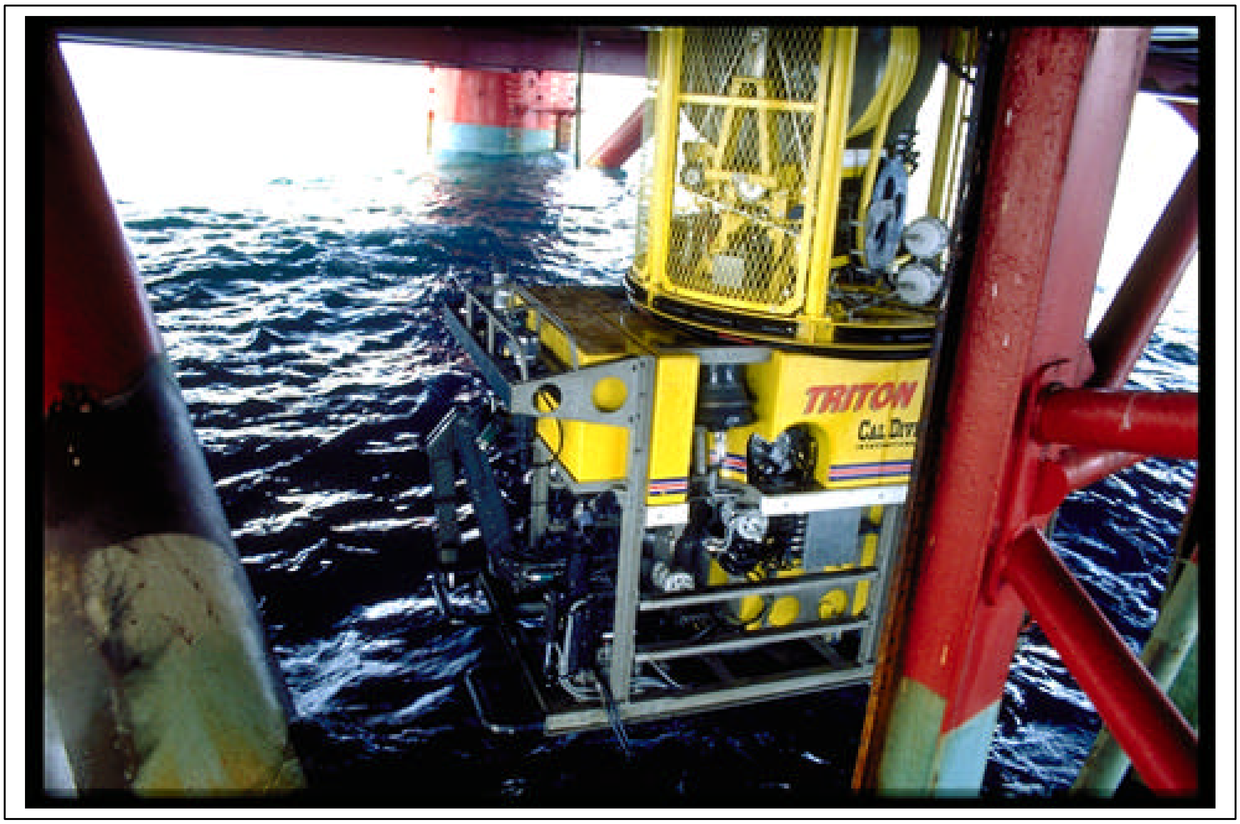
Observation class ROV systems will be generally configured as follows:

- Tether management systems (tophat or cage)
- Color zoom and low light or SIT video cameras
- Sector scanning sonar
- Low pressure water cleaning system or brush for cleaning of seals and bullseyes
- Altimeter and depth transducer
- Lighting
- Auto functions

Work class ROV systems will usually be configured with the standard suite detailed above, plus the following additional tools and sensors:

- 5-function or heavy duty 7-function rate manipulator for moving payloads, manipulating the drill string and for holding the ROV on a stable platform

- 7-function spatially correspondent manipulator for fine manipulative tasks, hot stab deployment and varying camera angles (with mini manipulator mounted camera)
- Variable torque tool for actuating valves and releasing subsea hardware locking mechanisms
- Hot stabs for fluid transfer and valve actuation
- AX/VX ring tools for replacing seal mechanism on Blow Out Preventers (BOPs) and Lower Marine Riser Packages (LMRPs)
- Override tools for engaging and disengaging guidelines.
- Guillotine and chopsaws for contingencies



Manpower

As the greater percentage of drilling activities are supported by ROV systems providing a contingency service, crews are then typically provided at minimum levels. In fact, many operators as policy do not specify ROV or diving services at all, choosing to rely on experience, drilling contingencies and, in some cases, good luck!!

The norm, however, is to provide ROV services on a 12-hour basis with a 3-man crew, comprised of 1 ROV Supervisor and 2 ROV Pilot/Technicians, for work class systems and a 2- or 3-man crew for observation class systems. Generally, this crew would be available around the clock on an as required basis.

Typically, the crew would be required to rest a minimum of six hours between shifts; however, this is often stretched or even abused during hectic periods, primarily during spudding (commencement of well) and plug and abandonment (completion of well).

During completion operations, the scenario changes considerably as the ROV remains on critical path operations throughout this intensive phase. Generally, operators require a 6-man crew providing full 24-hour coverage.

Today's modern semisubmersible in many cases provides far more than traditional drilling and completion services. They often undertake a number of construction based tasks during the completion phases of subsea production systems.

In these instances, the ROV crew may be required to measure and install jumpers connecting trees to the subsea manifold, land and connect trees, and provide a multitude of other services required to bring wells on stream. During these activities, it is not uncommon for the rig to retain the services of two ROV systems, a crew of 12 (4 Supervisors and 8 Pilot/Technicians) and a Project Superintendent.

Duration

Drilling support programs can vary from a 7 to 10 day operation supporting the completion phase of a well, up to 3 to 5 years supporting a multitude of wells in possibly a multitude of geographical locations.

Typically, this is the choice of the operator (oil and gas company) and is usually based upon a number of the following issues:

- Philosophy and policy of the operator
- Complexities of the wells
- Economies of scale
- Space restriction onboard
- Accommodation constraints
- Water depths/tree configurations
- Regulatory authorities
- Budgets
- Supply and demand

In many cases, the ROV system has been designed into the drilling rig and, as such, the contractor will remain onboard for many years.

The typical time frame to drill an exploratory well is between 30 and 90 days. This varies greatly depending on water depth, drilling target depth (TD), well complexity and the drilling platform used.

Contracting/Commercial

Generally, ROV services are contracted between the operator (oil and gas company) and the ROV contractor directly. In rare cases, the drilling contractor may be requested or may offer to provide these services as part of his overall scope of supply. This is rare, primarily because drilling contractors are averse to accepting the risk of ROV downtime that may cause drilling downtime and its associated financial penalties.

Drilling support is seen as the “bread and butter” of ROV oilfield services. Primary reasons for this are the obvious ones:

- Long-term steady revenue
- Low risk to equipment
- Steady employment of personnel

Less obvious reasons are:

- Lower specification of equipment is generally required
- System is not generally on critical path
- The skill base of personnel can be diluted
- Sound training ground for personnel

Drilling operations, however, do not normally lead to value added revenue opportunities and generally attract lower rates than other activities. Some ROV contractors shy away from this business for these reasons.

Installation and Construction

General

If drilling support is a walk in the park for ROV contractors, then installation and construction is the triathlon of all the support services in the oil and gas ROV industry.

These activities are the most demanding, require the most capable equipment and insist on the greatest experience and skill of the ROV crew.

Installation and construction support is the realm of the work class ROV operating on the critical path as a key element in the development program. Observation ROV systems are often utilized in this area, but only in a support role to the work class system.

Installation and construction support designated the use of ROV systems before, during and after the installation of platforms, subsea production systems and others, and the installation, laying, hook-up and commissioning of flowlines, trunklines, export lines, cables and umbilicals.

During these operations, the ROV spread may be deployed from a wide variety of vessels dependent upon the scope of work and the preference of the construction company.

The ROV may be installed on the construction barge or lay vessel (see earlier figures), which are very stable platforms but allow limited access to the work site for some tasks, such as observation of pipeline touch down.

For this reason, many ROV support operations are undertaken from vessels operating independently of the barge or lay vessel.

In their extreme, they may be Dynamically Positioned (DP) vessels in excess of 280 feet long, typical of North Sea operations, to non-DP multi-service vessels from 180 feet, which are commonly used in the Gulf of Mexico and Asia Pacific.

***Witch Queen* (right)**

Scope of Services

With the improvement in work class ROV capabilities, added system redundancy and greater water depths, companies have increased the scope of work that ROVs are expected to undertake as routinely planned tasks. Typical requirements are:

- Pipeline/platform pre-installation survey
- Observe pipeline start-up procedures
- Monitor installation of pin piles
- Run, connect and cut cables
- Pipeline touch down monitoring
- Installation of mattresses at pipeline crossings
- Dredging and pumping operations
- Transport, position and recovery of positioning transponders
- Monitor piling operations
- Aid in grouting activities
- Jumper installation
- Connect and release shackles and hooks
- Operate valves for flooding and inhibitor
- Deployment and recovery of pipeline pigs during pigging and gauging operations
- Cutting and removal of bolts, straps, bands and clamps
- General and detailed contingencies

The above are all seen as routine installation support tasks these days. Project specifics call for a wide range of more complex and demanding activities requiring forward planning, detailed procedures and purpose built ROV tools.

System Configuration

Work class ROV systems deployed successfully on installation and construction projects are living up to their name. Typically with power plants of 100 hp or greater, they are the most modern and capable class available.

Unlike drilling support systems, construction class systems require significant built-in redundancy, intelligent diagnostics, a multitude of auto functions and, most importantly, efficient and effective use of available power.

Systems also need the availability of additional hydraulic circuits for tooling functions and must have the ability to carry and maneuver heavier payloads.

Work class systems are typically configured as follows:

- Tether management systems (tophat or cage)
- Color zoom and low light or SIT video cameras
- Sector scanning sonar
- Low pressure water cleaning system or brush for cleaning of seals and bullseyes
- Altimeter and depth transducer
- Lighting
- Auto functions
- 5-function or heavy duty 7-function rate manipulator for moving payloads, manipulating the drill string and for holding the ROV on a stable platform
- 7-function spatially correspondent manipulator for fine manipulative tasks, hot stab deployment and varying camera angles (with mini manipulator mounted camera)
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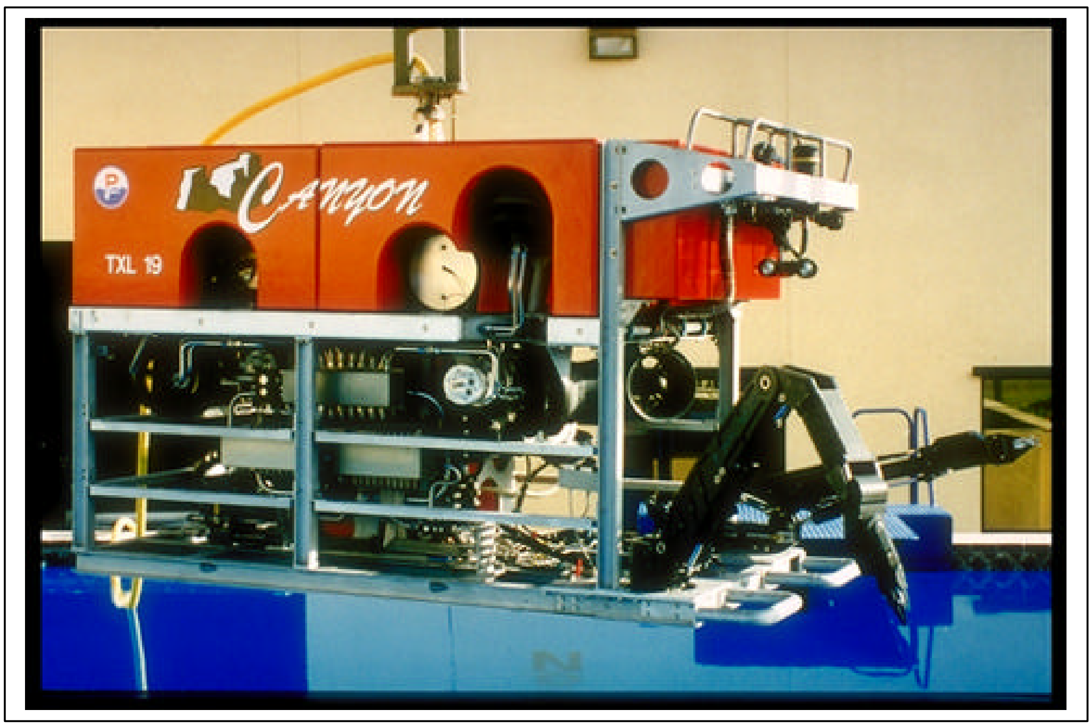


Manpower

Typically, installation and construction support programs are manned under 24-hour operations. If the vessel engages only 1 ROV, a standard crew would consist of 2 ROV Supervisors and 4 ROV Pilot/Technicians, providing for 2 crews on 12-hour rotations on opposite shifts. If the scope of work is particularly demanding, a Superintendent may be added as a Project Manager.

Larger offshore developments regularly call for multiple vessels operating in conjunction with the installation barge or vessel. In these instances, there may be any given number of primary ROV systems engaged in the program and the crew and Superintendent/Project Management makeup will increase exponentially.

The true differential between drilling support manpower requirements and that of installation and construction support is in the planning stage. During a large construction program, there may be up to three or four vessels operating in harmony to complete the given work scope. The ROV will almost always be on the critical path and, therefore, it is essential that detailed procedures are written, practiced and adhered to. Accordingly, this will ensure the efficiency of the entire operation. This requires the successful ROV Contractor to have engineering, planning and project management resources in place during preplanning.

Duration

Installation and construction projects obviously vary in size and, as such, their duration varies accordingly. However, many construction companies choose to award ROV contracts on a seasonal basis, utilizing the services of the same ROV contractor for all activities in the season or supporting a particular barge or installation vessel.

Often, this is done under a Master Service Agreement or Approved Supplier Agreement, where all contractual terms and conditions are pre-agreed and a set of standard rates is applied.

As the provision of reliable and efficient ROV operations is critical to successful construction programs, some Contractors simply employ the same ROV contractor, routinely insisting upon the same equipment and crews to support their various vessels each season.

Contracting/Commercial

In most cases, the ROV services contract is maintained between the ROV contractor and the installation contractor and, more often than not, included in the installation contractor’s lump sum price to the operator (oil and gas company).

Occasionally, the operator will require an independent ROV service operating under a contract to them, primarily as a “bird dog” or quality assurance exercise.

The installation and construction industry offers the ROV contractor the largest scope for value added services.

In general, operations are 24-hour based, increasing revenue for added manpower, and there is a greater opportunity for intervention services and project management.

The greatest incremental opportunity is in the provision of third party services. The ROV contractor is very often required to provide the ROV vessel, survey and positioning and a multitude of other services.

There is, however, increased risk in this arena and many ROV Contractors therefore choose to avoid it, offering services in drilling support and/or inspection only.

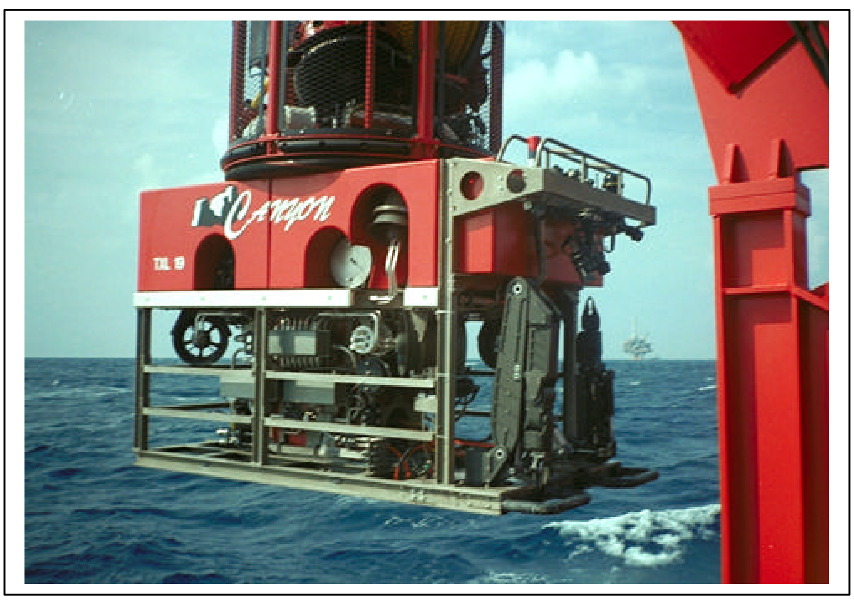
Inspection, Maintenance and Repair

General

Inspection, Maintenance and Repair (IMR) covers a wide range of activities from simple visual inspection to very detailed surveys. Industry typically categorizes inspection into “pipeline” and “platform.”

Pipelines are inspected in all cases immediately after they are installed to ensure they are laid within the specified tolerances and to determine if any damage occurred during the lay process. This is commonly referred to as an “as-built” or “as-laid” survey. The requirement to inspect pipelines regularly after installation varies greatly worldwide, with the North Sea and European sectors having the most stringent regulatory requirements.

Platforms are usually not inspected immediately after installation, though this requirement varies globally. In most regions, however, platforms do require inspection during their life cycle, either as an insurance or policy requirement of the owner or by decree of regulatory authorities. Additionally, platforms are inspected for damage after tropical storms, hurricanes, typhoons, etc. Again, platform inspections can be as simple as a visual fly-by of key areas of interest or a very detailed NDT (non-destructive testing) program.



Scope Of Services

Pipelines

Generally, when inspecting pipelines during as-built or scheduled inspections, you are looking for a number of anomalies that may require remedial action to ensure the line maintains its integrity. Primary issues are:

- Free spans (unsupported areas of spanning that can stress the line)

- Weight coat damage (loss of concrete coating that can affect the cathodic protection system)

- Presence of debris (that may cause damage or affect CP)

- Cable and pipeline crossings (unknown crossings that may not be properly supported)

- Anchor scours (possible damage from anchor activities)

- Depth of burial/cover (when pipelines have been trenched)

- To determine the pipeline position (verify position geographically)

Platforms

The following range of inspection activities may be required during a platform inspection:

General Visual Inspection (GVI)

This is the primary requirement of any platform inspection to determine:

- Marine growth deposits
- Locate areas of damage
- Locate and remove debris at the mud mat level
- Survey coating condition
- Visual inspection of anodes
- Cathodic potential measurements
- Splash zone inspection of marine risers
- Flooded member detection
- Integrity of clamps

Close Visual Inspection (CVI)

Undertaken when defects have been determined during GVI:

- Cleaning of weldments and close visual inspection
- Wall thickness measurements
- Photogrammetry of cracks in weldments or members
- ACFM or ACPD weld defect location

System Configuration

Pipelines

Generally, work class or survey class ROV systems are utilized to undertake inspections of pipelines, primarily because of the general requirement to carry any number of survey sensors and because they are required to operate in areas of current activities from a moving vessel. The following is a list of equipment that may be required in any given project dependent upon the specification of the client and the geographical location.

- Tether management system to reduce current and depth loading on the umbilical (not always preferred by some contractors)

- Color zoom and low light SIT video cameras

- Sector scanning sonar

- Auto function (pitch, roll, heading, depth and trim)

- Lighting

- Port and starboard articulated boom mounted cameras for viewing each side of the pipeline and investigating free spans

- Wheeled undercarriage for maintaining the vehicle on the pipeline in a stable mode

- Odometer for measuring linear progress along the pipeline

- Pipetracker for maintaining the ROV over buried pipeline and for measuring depth of burial.

- CP system to measure the cathodic potential along the pipeline and to carry out anode and bare metal pipeline stabs to measure direct potential.

- Dual head profiling system to determine the position of the pipeline in a trench, determine free spans and aid in the measurement of depth of burial.

- Doppler log to measure speed of the ROV and aid in the positioning of pipelines and pipeline features.

- Motion sensor to aid in the “smoothing” process during post processing of survey and navigational data.

- Surface navigation to determine accurately the position of the vessel geographically (usually by differential global positioning – DGPS).

- Acoustic navigation to accurately determine the position of the ROV and its sensors in relation to the surface vessel.

- Online and post processing integrated software for collection and correlation of all survey and navigational data into a detailed report.

- Gyro mounted on the ROV to accurately determine heading of the ROV.

- Other sensors required may include:

  - Swathe bathymetry for seabed topographical mapping in 3D

  - Side scan sonar for survey of the seabed features adjacent to the pipeline

  - Sub bottom profiling for providing geophysical details of the seabed under the pipeline

Platforms

Again, the specifications for platform inspection vary greatly and the following is a list of equipment that may be required on a given campaign:

- Tether management system to enable horizontal excursion to the work site and retain the umbilical vertically and away from obstruction.

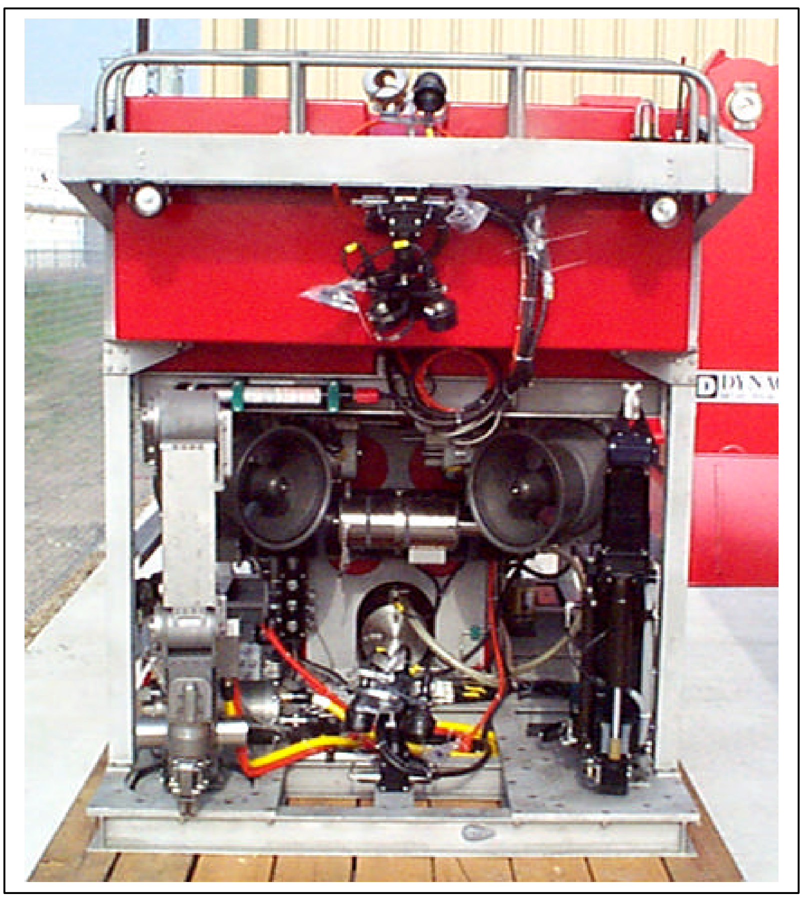
- Color zoom and low light SIT video cameras

- Lighting

- Contact CP system for determining cathodic potentials of anodes

- Sonar for navigation

- Auto functions (heading, depth, trim)
- Manipulator for clearing away lines, ropes, etc., and for mounting of probes
- Marine growth measurement graduated probe
- Still photography capability (35 mm, digital or video grabber)
- Flooded member detection equipment to determine gross damage to members
- Low and high pressure water blasting or grit entrained cleaning equipment for the removal of marine growth and black oxide for weldment inspection
- ACFM or ACPD equipment for crack detection
- UT devices for wall thickness measurement
- Torque tools for the tightening of riser clamps



Manpower

Pipelines

The higher the specification of the project, the greater the crew requirement tends to be. On a North Sea style operation, a crew working on a 24 hour cycle will typically consist of:

- 1 Project Superintendent
- 2 ROV Supervisors
- 4 ROV Pilot/Technicians
- 2 Data Coordinators
- 4 Online Surveyors
- 4 Offline Surveyors
- 2 Process Engineers
- 2 CP Engineers

These numbers do not include the vessel crew and DP operators required.

Platforms

The requirement for 24-hour operations during platform inspection varies worldwide and is often dependent upon whether the inspection is being undertaken from a vessel or directly from the platform. It is also determined by the client's preference to improve data quality by working only in daylight conditions. A typical 12-hour crew would consist of 1 ROV Supervisor, 2 ROV Pilot/Technicians and 1 Inspection Engineer. This can increase if cleaning systems are engaged. For 24-hour operations, the requirement is doubled.

Duration

For both pipeline and platform inspection programs, task duration obviously varies with the scope of work. Often, however, construction companies will engage ROV contractors seasonally to undertake all of their ROV surveys, supporting a lay barge/ vessel throughout the year.

In the North Sea, ROV contractors mobilize a complete spread of vessel, ROV survey and positioning at season commencement and bid on a significant number of projects for the year, hoping to "piggy back" from one job to the next and maximize the utilization of their spread.

For platform inspections, these are typically done on a campaign basis where an operator (oil and gas company) specifies a number of platforms to be inspected within a given time frame.

In some regions, operators have programs that require a spread to be engaged continuously on an annual basis, though this is quite rare.

Commercial/Contractual

Pipelines

“As-built” or “as-laid” surveys are generally undertaken on a daily rate basis as part of the support for barge and lay vessel activity. The scope of supply of the ROV contractor can simply be the provision of the ROV and personnel, or may include the vessel, survey and positioning, and a number of other third party services. This is normally determined by the client or by circumstances.

Planned inspections are typically done on a lump sum basis, often on a “per kilometer” base or a price per pipeline. Mobilization and demobilization are often reduced as projects are done consecutively, thus cost is shared between the operators.

A significant part of the survey price is the report. Typically, a report would include the following:

- Charts in 1:5000 scale (or similar) that include:

  - Horizontal profile of the pipeline
  - Vertical profile of the pipeline
  - CP profile
  - Anomaly location

- Video tapes, logs and still photos
- Survey of events
- List of resources
- General criteria
- Findings and recommendations

This, in essence, is what the client is paying for.

Platforms

Platform inspections are carried out under a mixed arrangement of daily rates and lump sum. Contractors generally prefer daily rates. Although the work is no more complex than pipeline surveys, time frames to estimate work tasks are very difficult to judge and the risks of overrun are greater. This is often compounded when performing inspections in parallel with a manned diving campaign.

AUVs

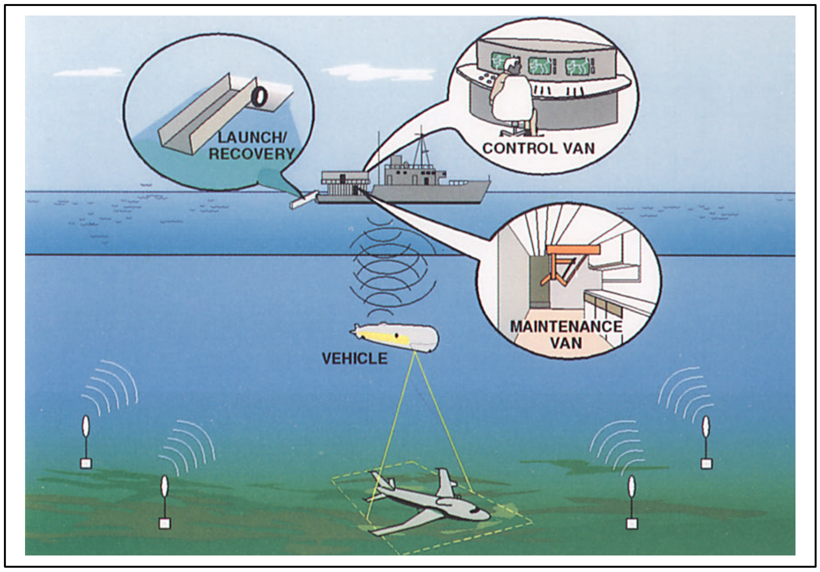
AUVs are currently in their infancy, although some have demonstrated some real capability for performing tasks in the ocean. The following is a list of missions or work tasks that AUVs have performed or could be used for in the future:

- Pipeline inspection and survey
- Pipeline and cable route survey
- Subsea oil field inspection and intervention
- Under ice exploration and mapping
- Coastal survey and mapping
- Fiber optic cable laying
- Acoustic and optical array deployment
- Sensor deployment
- Security sentry
- Product test bed
- Hydrodynamic testing
- Operational demonstrations
- Mine reconnaissance
- Mine countermeasures
- Search
- Hydrographic survey
- Physical and chemical oceanographic survey
- Biological specimen collection
- Fish count
- Coral reef survey
- Hazardous dump site survey
- Responding to episodic events (volcanoes, earthquakes, etc.)
- Covert reconnaissance
- Submarine offboard sensor
- Long-range (stealth) weapon
- Harbor surveillance
- Ship hull inspection
- Drug interdiction
- Environmental monitoring

Tasks that have been successfully demonstrated by AUVs, which will be discussed in more detail, are:

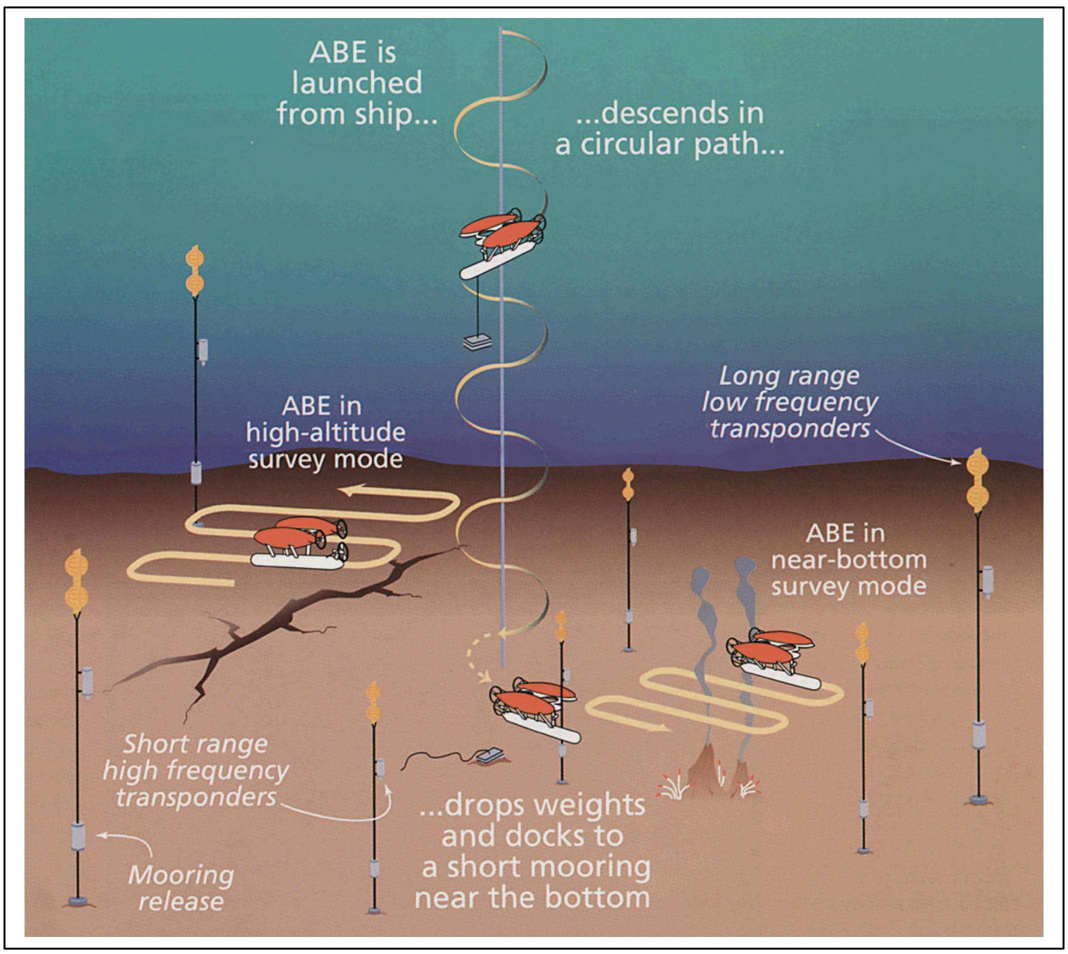
Search and Survey

The military first proved the effectiveness of using an AUV for performing searches for lost objects in water depths to 19,685 ft (6,000 m). This was done by the US Navy's Advanced Unmanned Search System (*AUSS*) described earlier. Like most systems in use today, AUSS is semi-autonomous, i.e. tether-less. It is supervised via an acoustic link that allows it to receive commands and transmit images of the seafloor to the surface ship above.



***AUSS* operational configuration (right) (Courtesy of the U.S. Navy)**

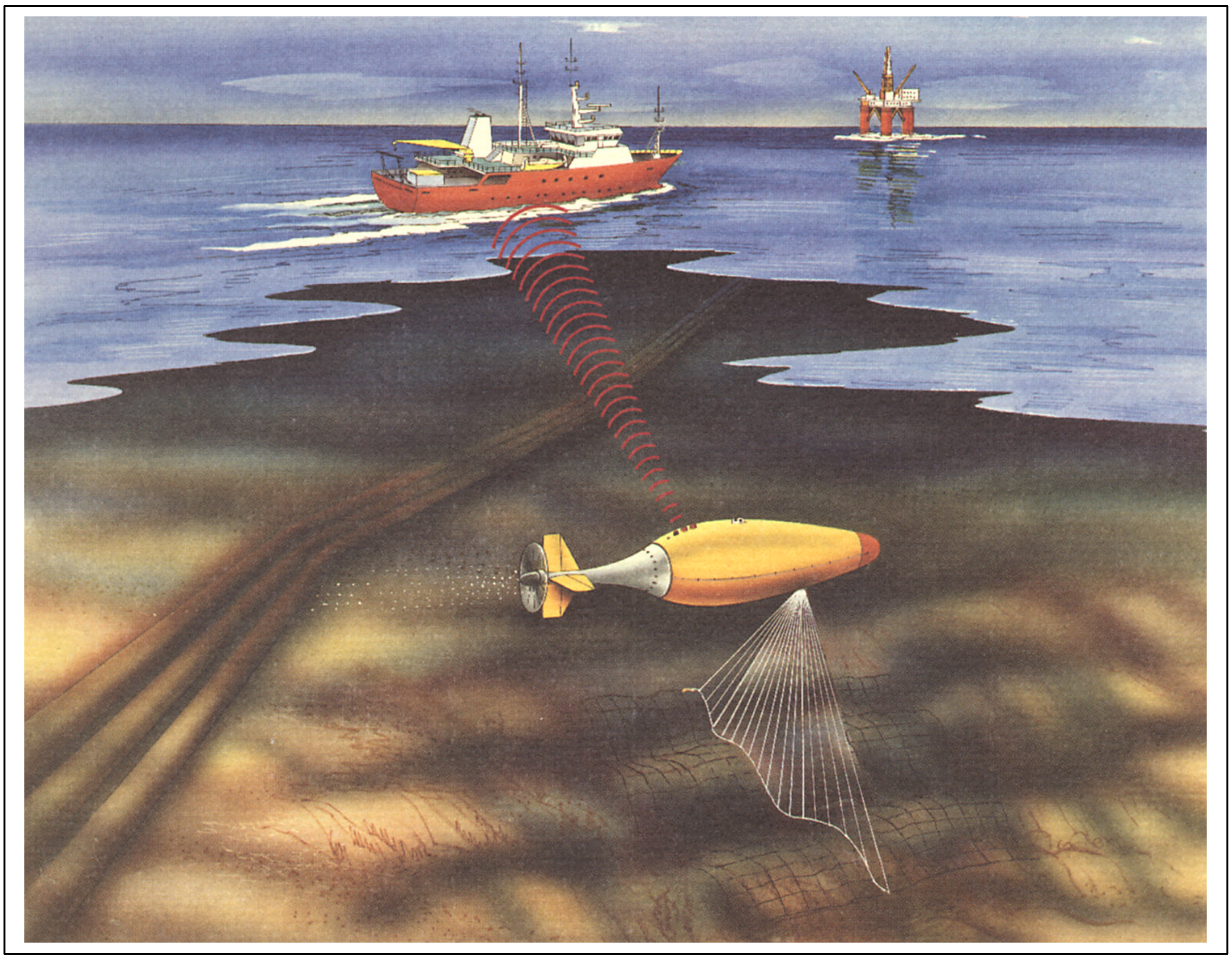
Woods Hole Oceanographic Institution's *ABE* AUV has demonstrated the ability to perform very deep local surveys of areas to be studied over long periods of time.



***ABE* operational configuration (Courtesy of WHOI)**

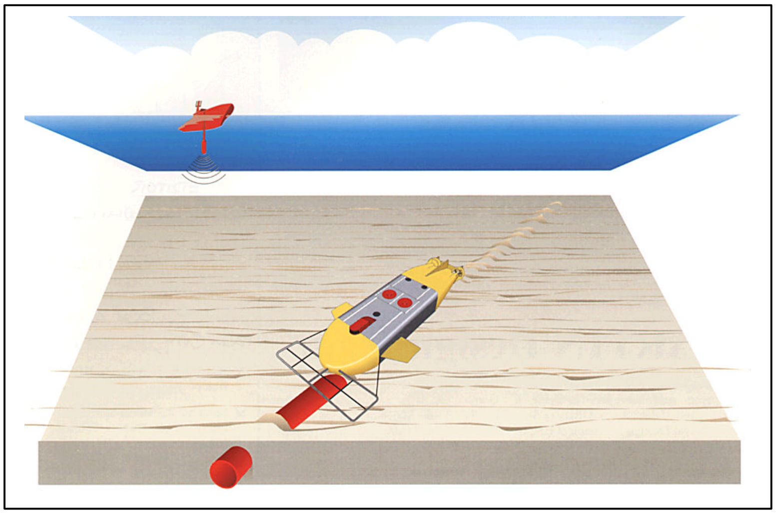
Both MIT (*Odyssey* AUV) and Florida Atlantic University (*Ocean Voyager II/Explorer* AUVs) have demonstrated the ability of multiple AUVs to work together to multiply the data collection capability of underwater systems. In addition, *Ocean Voyager II* has integrated and demonstrated the ability to perform video and side scan sonar surveys by an AUV. The *Odyssey* AUV has demonstrated the ability to dock autonomously.

More recently the first oilfield application was completed by the *Hugin* AUV, which performed an extensive route survey for Statoil in the North Sea. This vehicle will be able to perform work to depths of 6,562 ft (2,000 m) in the future.



***Hugin* performing survey operations**
(Courtesy of Kongsberg Simrad)

In the future, AUVs like *Hugin* and *Martin* will conduct pipeline surveys, greatly reducing the time and cost required to perform this work.



***Martin* performing a pipeline survey (Courtesy of Maridan)**

Cable Laying

Several AUVs, including Lockheed Martin's *MUST Lab* and I.S.E.'s *Theseus,* have demonstrated the capability to lay long lengths of fiber optic cable in the ocean and, in the case of *Theseus*, under ice.

Towed Systems, Bottom Crawlers, Hybrids and Plows

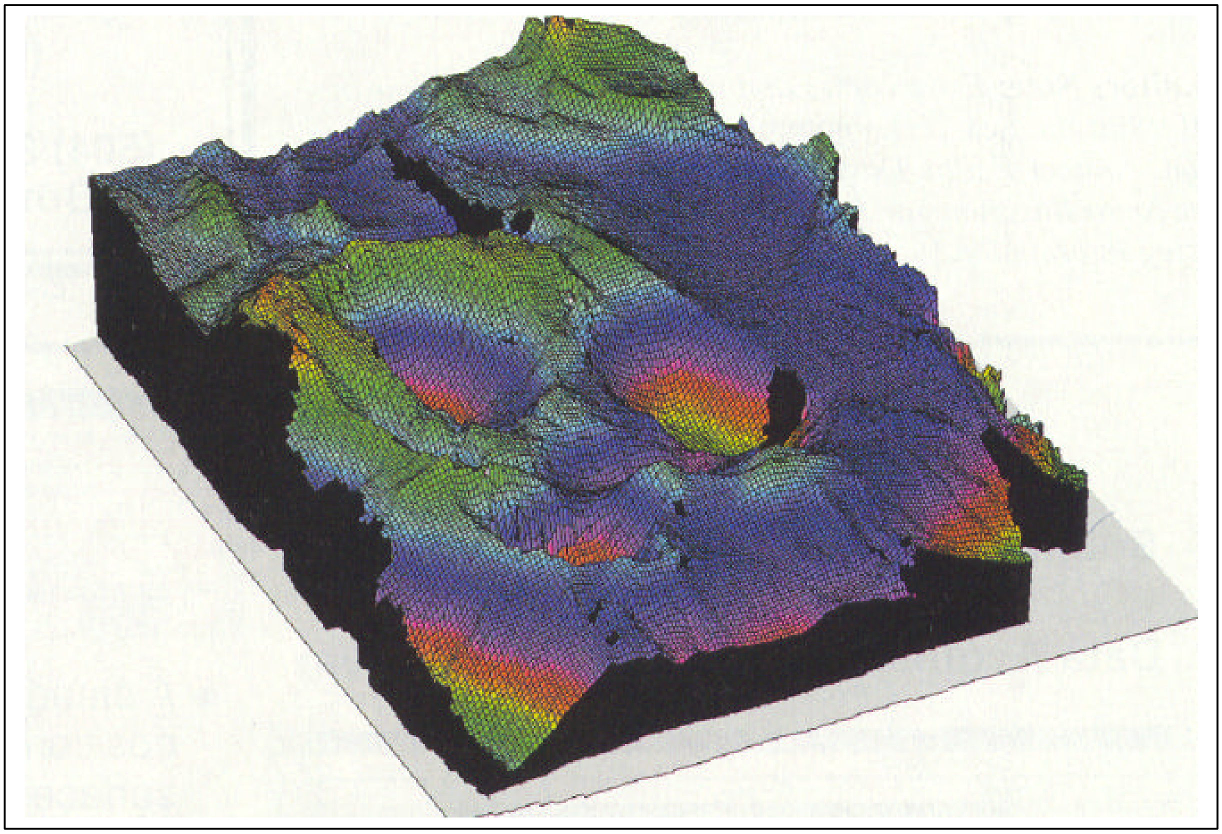
Mid-Water Survey

Towed (mid-water) systems are primarily used for conducting search or survey operations and can carry a variety of sensors for detecting objects or features on the seabed. These include cameras, laser imaging systems, sonars, and magnetometers. Typical missions include large area surveys, route surveys, lost object search, and sea floor mapping.

One area that should not be overlooked is the use of towed sonar systems for bathymetric surveys. Systems such as the UK's GLORIA (Geological Long Range Inclined Asdic), operated by the Southampton Oceanography Center, combine high quality side-scan sonar and swath bathymetry data with rapid ground coverage to map the seafloor around the world. GLORIA was commissioned by the United States Geological Survey (USGS) to map the US Exclusive Economic Zone (EEZ). Over a 7 year period, GLORIA mapped 2.7 million square miles (7 million square kilometers) of the US EEZ.

GLORIA is 25.2 ft (7.75 m) long, 2.1 ft (0.66 m) wide, 2.7 ft (0.81 high) and weighs 2.04 tons in air. The transducers are made up of 2 rows of 30 elements on each side. Array width is 17.5 ft (5.33 m), has a horizontal beam width of 2.7 degrees and a vertical beam width of 30 degrees at a fixed inclination of 20 degrees below horizontal. Sonar frequency is 6.3 kHz (starboard and 6.8 kHz (port). Maximum range of the system is 14 mi (22.5 km) on each side, giving a typical coverage of 7,000 sq-mi (18,000 sq-km) per day at a tow speed of 9 knots (16.7 km/hr).

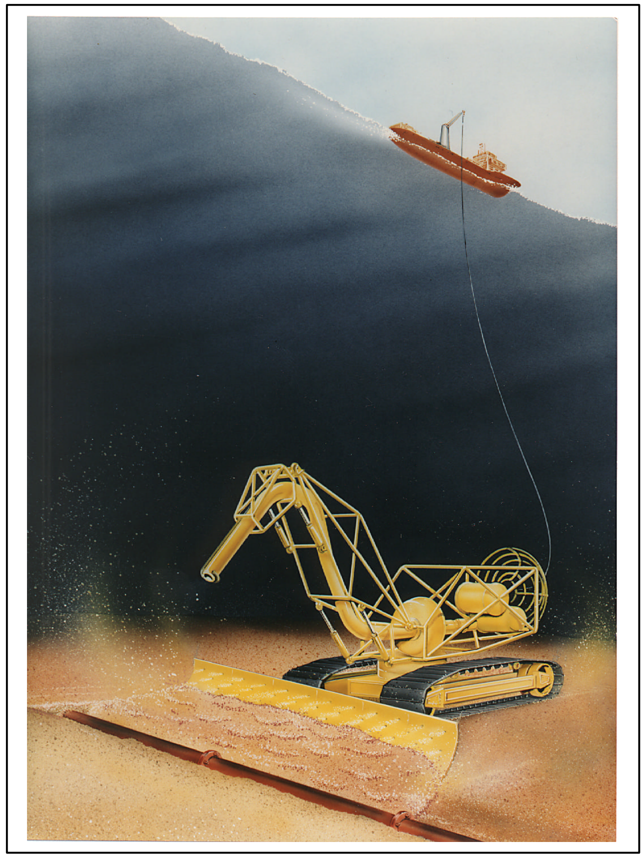
There are a large number of such vehicles in use today conducting cable route surveys, searching for lost objects, performing disposal-site search and identification, supporting offshore sensor installation, pipeline siting and installation, ocean mining and various other projects. When this data is combined with state-of-the-art software programs, the result can be dramatic 3-D color enhanced displays of the search area. As an example, the following figure was produced by Science Applications International Corp. (SAIC) using their *FOCUS-1500* ROTV (remotely operated towed vehicle). The figure represents the summit area of the Loihi Seamount off the Island of Hawaii, representing an area of approximately 4 sq-mi (10 sq-km).



Telecommunications Support

Bottom crawlers evolved from land-based tractors, from which much of the technology developed was applied to subsea systems. However, the problem of working on the sea floor turned out to be much more difficult and in some conditions severe. Holes, steep grades and soft soil have prevented some designs from being successful. The systems that have prevailed have learned from other's mistakes. Crawlers work best on firm, flat seabeds and will not work under all conditions.

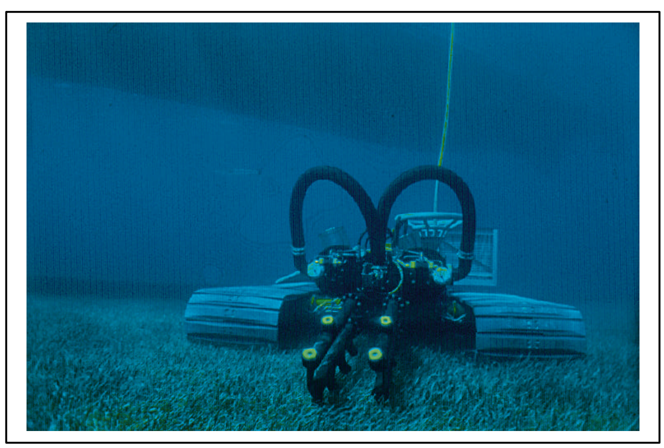
Pipeline burial operation (right)



The greatest success to date for the subsea crawler has been in shallow water work, primarily in telecommunications support. These crawlers are small enough to be deployed from a barge or small ship and average about 100 hp. They are typically capable of using multiple tools that include water jetters, chain trenchers and rock saws. These can be changed out quickly to adapt to a given seabed condition. In some cases these systems must cut through solid rock or coral to reach the beach.

Crawler rock trenching operation (below) (Subtec STBS Ltd)

Telecommunications support has included such tasks as shore end completions and cable burial. Another area of moderate success for crawlers has been in shallow pipeline inspection work.



Crawler cable jetting operation (above) (General Offshore Corporation)

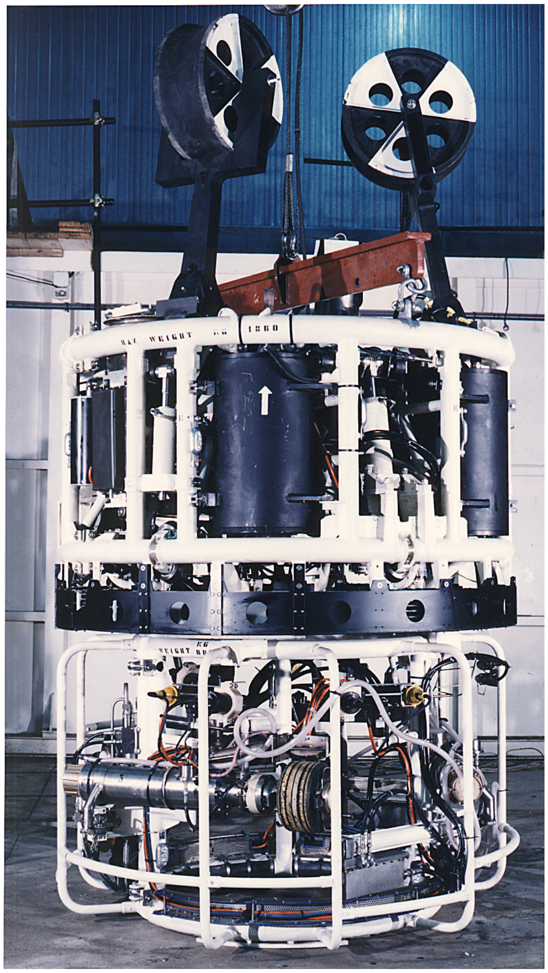
For the deeper cable laying work, to about 6,562 ft (2,000 m), the heavy plows are used to bury the cables and backfill the trenches.

***Plough* and handling system aboard ship**
(Soil Machine Dynamics Ltd.)

Miscellaneous Tasks

Hybrid vehicles essentially cover all other jobs that conventional systems cannot perform or cannot be easily configured to perform. Some of these applications are:

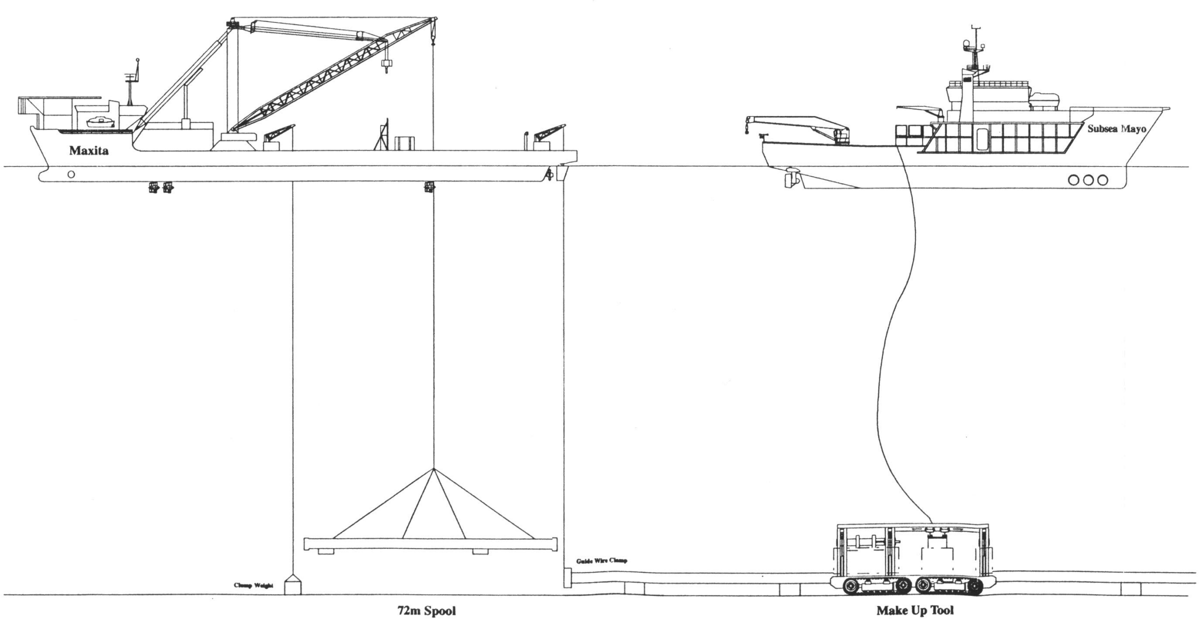
- Bottom sampling
- Treasure hunting
- Stone dumping
- Riser inspection
- Tunnel inspection
- Submarine rescue
- Large object salvage
- Diverless pipeline repair
- Pipeline installation
- Combination towed/ROV systems

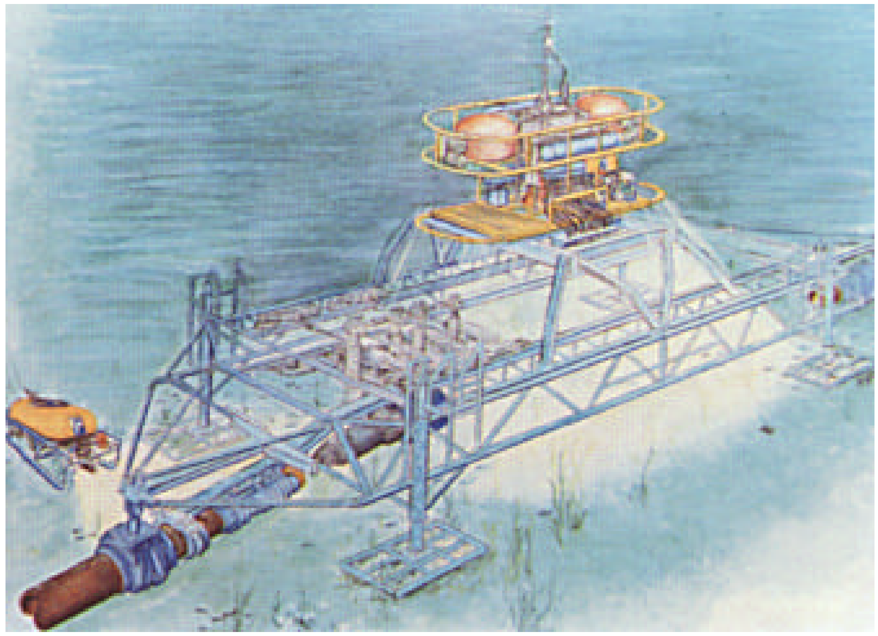


Technomare SpA's riser inspection ROV (left)

Some systems have been combined to perform multiple functions such as Deep Sea Systems International's combined towed vehicle *TSS-1000* (see figure next page) and *MiniROVER* ROV. Systems like these allow a wide area search or survey to be performed and then an ROV can be deployed to perform a detailed survey of the area of interest.

Pipeline installation operation (below)



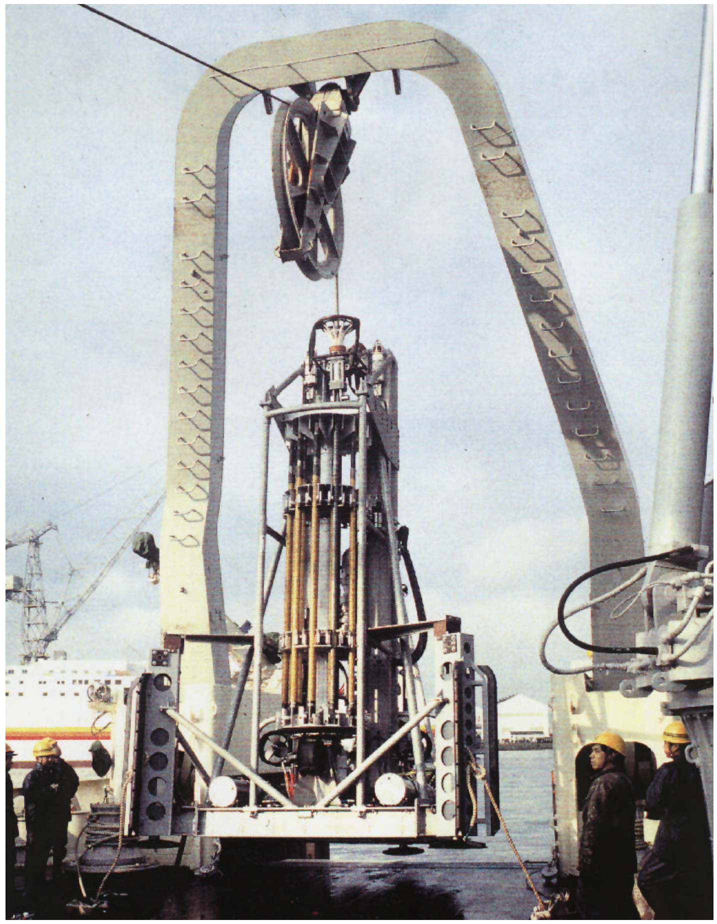


Remote pipeline repair operation (right)

Deep Sea Systems International's Towed *TSS 1000* with *MiniROVER* ROV onboard (left)

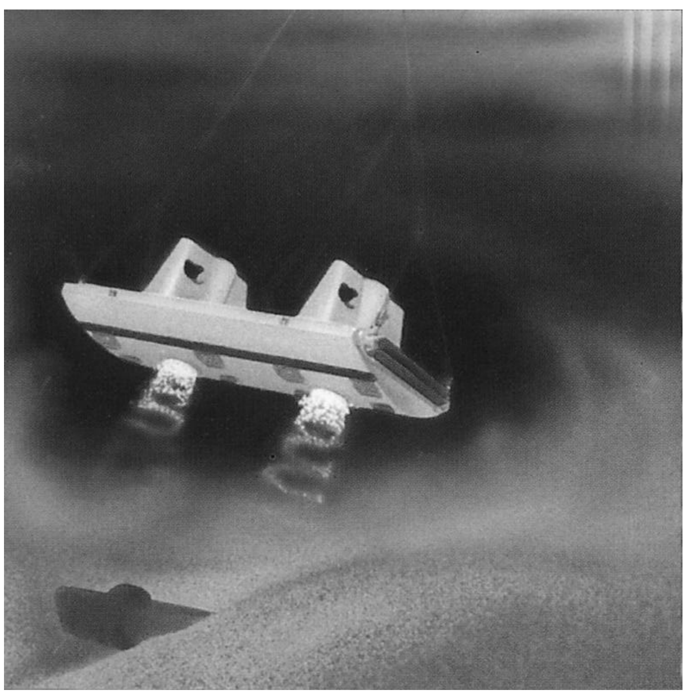
In other cases, it has become advantageous to add thrusters to just about anything that is to be lowered and positioned in the ocean. An example of such a device is the corer (following page), which can be flown to several locations within a specified area and take core samples of the seabed.

Williamson & Associates Inc.'s coring system with thrusters (right)



Other systems have been designed specifically for pipeline burial work such as the *Winged Excavator*.

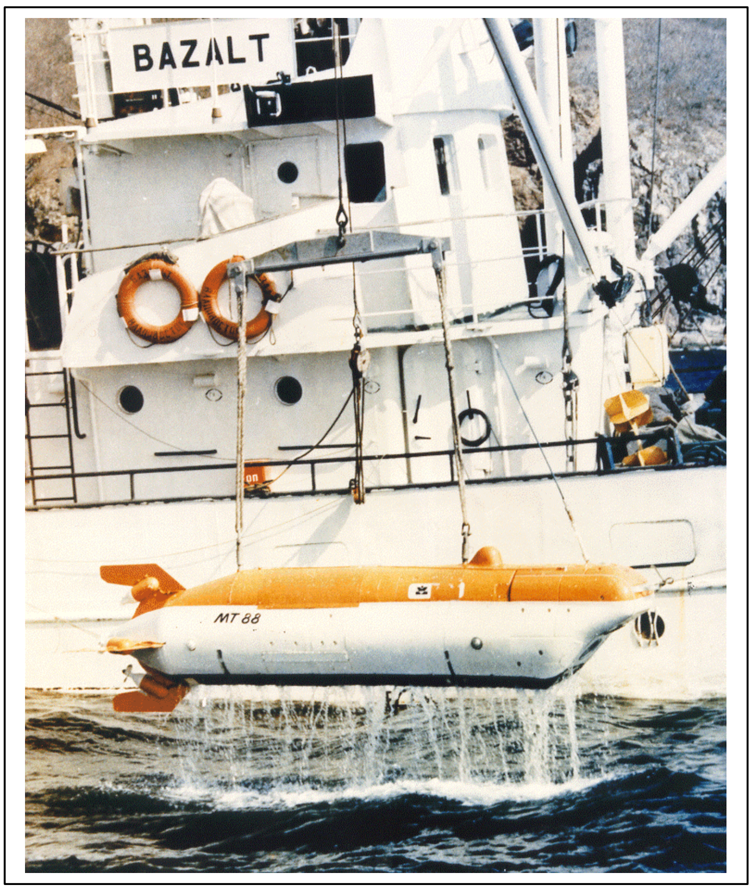
SILT (UK) Ltd.'s *Winged Excavator* (below)



MILITARY

Earlier in this publication we discussed how the military applications for unmanned underwater systems provided the genesis for unmanned underwater vehicle technology. In those early days, such systems were developed primarily for undersea observation and the recovery of lost devices and weapons. Since then, the technology has moved steadily forward, bringing with it a directly related increase in operational capability. Unfortunately, this increase in capability brings with it a higher price tag–especially in the military–a fact that may have initially slowed the acceptance of such advanced technology. And more recently, the change in the political climate around the world has caused a refocusing of what the military feels is the primary mission for such systems. This section will discuss the issues related to the military's use of unmanned underwater vehicles, present applications and the direction the military is considering in the future.

When the original Guidelines were written, the primary discussion of military applications for UUS was in the area of mine countermeasures, where tethered ROVs were being applied. Along with that was a continuation of research into recovery technology and the fledgling arena of untethered vehicles used for search. At that time, the US Navy's eyes were focused on the depths of the ocean–the magic number being 20,000 ft (6,096 m), where 98 percent of the ocean floor could be reached. In the US military at that time, there was a need to dominate all aspects of undersea search, work, and recovery to such full ocean depths. It was a critical need, if for no other reason than to remain one up on the perceived threat from the Soviet Union.



In those early days, there was no knowledge of an obvious undersea vehicle program ongoing in the Soviet Union. That soon changed as the Soviet's concern with the deep ocean and their capability to reach it was unveiled. Unclassified presentations on their programs in unmanned undersea systems, such as those at the Institute of Marine Technology Problems in Vladivostok, where the *MT 88* autonomous vehicle (see photo, previous page) was developed, along with many others, soon became common at international conferences.

Although the US and Soviet Union may have led the pack, Europe was not idle. With the transition of ROV technology from the US to Europe in the 1980s, many other vehicle developers emerged, primarily to support North Sea oil fields. Along with that was the maturation of the technology and subsequent application to mine countermeasures. The once dominant *PAP* vehicles from France began to see others arriving such as Pluto from Switzerland, *Pinguin* from Germany, the *Eagles* from Sweden and many others. Although some limited developments were pursued for deeper application, such as the rather unsuccessful Towed UnManned Submersible (*TUMS*) developed for the Royal Navy's *HMS CHALLENGER*, mine countermeasures (MCM) was basically the focus of military applications for some time, not the deep ocean thrust that existed in the US and the Soviet Union.

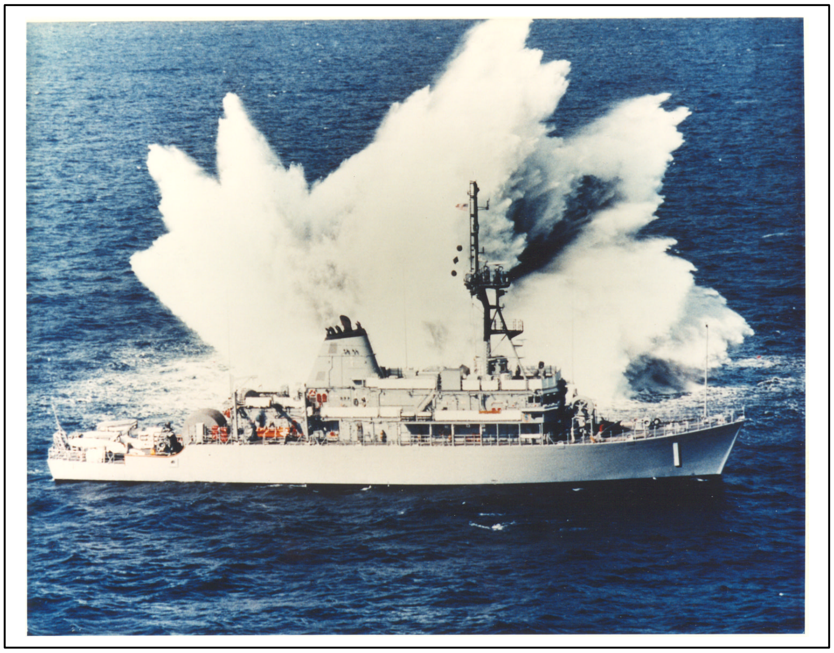
In recent years, a redirection of future military system requirements has been caused by two significant events; the first was the end of the cold war, and the second is the potential of hostilities with smaller countries that could wreak havoc through terrorism or unconventional warfare techniques. Driven by these changes, the US Navy began to rethink its "at sea" strategy and a new focus on littoral warfare began to dominate. MCM became critical–not only for surface ships, but also for submarines. If future battles were to be fought along world coastlines, with mobility a key factor, then safe operating areas needed to be found or established. Thus came one of the biggest changes in military strategy regarding unmanned systems.

What had once been discussed only behind closed doors–the use of unmanned vehicles deployed from submarines–was not only out in the open, it was on the World Wide Web. In the US, major moves were made to solicit the development of "offboard sensors" for use from submarines. Contracts were awarded for the NMRS (Near Term Mine Reconnaissance System) and the LMRS (Long Term Mine Reconnaissance System). The threat had changed and the NMRS, LMRS and other versions of shallower water systems began to achieve a foothold in the US Navy.

In Russia, where the most significant unmanned undersea systems of the former Soviet Union were developed, the trend moved from secret military applications to private enterprise, as most of the institutes moved into a financial fight for survival. The cold war had ended–the game and the rules had changed.

The following sections on Mine Countermeasures, Search/Recovery, and Intelligence, Surveillance and Reconnaissance will describe the systems that have been, and are being developed, for the military.

Mine Countermeasures



The threat of mine warfare has forced navies around the world to rethink their approach to the subject. The damage of two US warships in the recent Gulf War by WWII mines that were placed in the area by small craft is a good example. The adages that "every ship is a mine sweeper once" and "a single mine can ruin your whole day" lost their humor after those incidents–at least in the US Navy. The wisdom of traditional approaches, such as towing sweep gear and other devices through the water from ships to set off mines, was being reconsidered. Especially when taking into account the sophistication of today's mines–or the lack of sophistication of a few tossed in the water to float dangerously on the surface. But change in the military is evolutionary, not revolutionary, and although helicopter MCM with towed sleds, and deployment of advanced unmanned search systems provided much safer approaches, the primary focus was still on the development and outfitting of fleets of MCM ships around the world.

MCM was also a problem for each country with a navy that would have to face the threat of mines on their own shores. Regardless of how strong and powerful a country's ships, if they can not be deployed, they are useless. The "old Navy" that virtually ignored the mining problem as if playing Ostrich–if you can't see it, it can't hurt you–was slowly replaced by a new cadre, more experienced and aware of the problem and the technology to solve it. The funds began to flow and new classes of ships began to emerge whose primary battery would be ROVs, tethered systems that would work in concert with powerful search sonars to locate and destroy mines–one by one.

Today, the US Navy is planning to spend upwards of $300M on advanced MCM systems, operated from helicopters, surface ships and submarines from 1996 through 2001. It appears that the theme of the first MTS remotely operated vehicle conference, ROV '83, has finally taken hold in the military–it is "a technology whose time has come."

Before addressing the unmanned undersea systems developed for MCM, let's define the problem more completely. The task of MCM, which includes the areas of location and neutralization, covers a range of depths–from maximum submarine depth to the near shore environment. With the realization that the task of locating and neutralizing mines on land has yet to be successfully accomplished by men and machines who can walk on the ground in a relatively benign environment, with access to every type of technology, then it is easy to understand why undersea mine warfare is a real problem. Even if the MCM systems can get the troops and equipment near the shoreline, how are the last several yards of mines, which are well hidden in the near shore environment, going to be cleared? This doesn't even take into account those on the beach, just above the waterline.

Divers used to be the only way to confront the near shore environment, but it is obvious that the explosive ordnance disposal (EOD) teams are not the solution. Even with the human touch, most of the mines can not be found due to the factors of surge, current, turbidity, weather, lighting, covertness and the overriding issue of time. Since this publication is for unmanned undersea systems, we'll ignore the techniques that divers use to try and solve the problem and discuss techniques that the Navy will hopefully use to keep the EOD teams safely out of harm's way.

The problem of MCM can be stated simply–find the mines and neutralize them–before they find you. Simple? Not quite. But let's assume that the advanced mine hunting sonars deployed by the ships, or other devices, have found the mines. They have used advanced computational algorithms to locate, and classify the targets as MLOs (mine like objects), picking them out of the clutter of false targets. The vehicle operators then have a map showing where the MLOs are, or as a minimum, a specific target has been identified. At that time the following sequence of events take place:

- The vehicle is launched from the MCM ship and guided to the vicinity of the MLO using the ship's sonar.
- The vehicle searches the area until the MLO is picked up with its sonar and/or TV, while maintaining an appropriate horizontal and vertical separation from the threat.
- The MLO will be investigated to determine if it is a mine or a false target.
- If the object is a mine, it will be inspected and a neutralization approach determined–either place a charge nearby to destroy it (on the bottom, attached to the mine or nearby on the cable) or attach a device to cut the cable.
- The vehicle will return to the ship, or at least to a safe area, and the explosive device will be detonated using an acoustic signal.
- The mine is hopefully destroyed or rendered inoperable by the charge, or it is released to float to the surface where it will scuttle itself or be destroyed by gunfire from the ship. It should be noted, however, that the latter method is finding disfavor in the military–a mine floating on the surface is a greater threat than one anchored to the bottom. It can be obscured by the weather or wave action and, assuming the "sharp shooters" find it, they must hit it from the deck of a rocking ship. Unfortunately, there are few Navy crewmen that are qualified as expert riflemen.

To accomplish the previous MCM scenario, a vehicle with a wide array of characteristics must be used. The vehicle should have:

- Good maneuverability in all directions to ensure the vehicle can stay away from the mine.
- The ability to operate in high currents, with the thrust to control cable drag at a standoff distance that will protect the ship should the vehicle set off the mine.
- Adequate payload and trim capabilities to carry heavy bottom charges and/or cable charges or cutters.
- Sensors capable of locating the mine and identifying it (TV, lights, sonar, etc.) without activating the mine.
- Suitable control and navigation sensors such as compass, auto depth/altitude/heading, etc.
- Low magnetic and acoustic signatures.
- The capability to meet mission requirements for shock, vibration, electro magnetic interference (EMI), etc., as defined by the user.

The latter is an area that warrants some additional discussion. The world's most expensive ROV used for MCM is probably the AN/SLQ-48(V), developed by the US Navy–the Mine Neutralization System (MNS). The MNS had to meet a severe set of military specifications and requirements, such as the shock tests shown to the left, which resulted in a very costly system. It also took nearly twenty years to develop and field, as do most modern military systems, and is costly to operate and maintain. It is an excellent system and a tribute to the developers, but, with today's shrinking military budgets, costly systems are hard to sell, regardless of their potential capabilities. However, the US Navy has recently adopted a policy that virtually eliminates the poorly used MILSPECS (military specifications) and is considering systems that are developed using more COTS (commercial off the shelf) hardware and/or NDI (non-developmental items).

In the area of MCM, the use of COTS and NDI has its merits, since the ROV is considered expendable–when compared to the ship or its crew. But if the ROV's signatures are such that it sets off the mine when it nears it, then it becomes virtually useless, since the operating platforms probably only have one or two of the vehicles onboard. Thus, there evolves a vicious design cycle, where the best compromise must be made concerning COTS, threat, signatures, cost, capability, etc. The systems that have been developed around the world to date cover a full spectrum of these issues, from low cost expendable systems to dedicated military devices. Several examples of conventional and non-conventional systems will be provided in the following paragraphs.

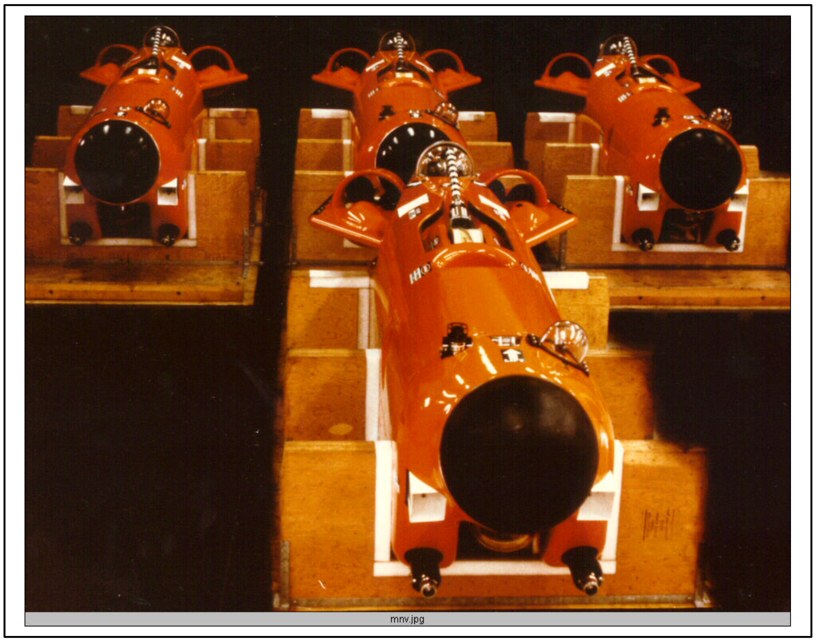
Conventional MCM Vehicles

Conventional MCM vehicles are considered those launched from MCM ships. Others, which include those launched from submarines, or new autonomous techniques to solve the near shore problem, will be discussed later.

The workhorse, and one of the oldest ROVs used in MCM, is the *PAP* system developed by ECA of France. The vehicle has evolved from the *PAP 104* with its bottom hugging drag weight to the fully capable *PAP Mark 5* with its 6 kt (11 km/hr) speed, 984 ft (300 m) depth, and 287 lb (130-kg) explosive charge payload capability. It is operated through an expendable fiber optic cable using an onboard supply of sealed lead acid batteries. The *PAP* line of vehicles has sold more than any other vehicle, of any type, in the world, exceeding 400 sold to over 14 navies worldwide.

France's
PAP 104

One of the most capable ROVs in the world for MCM is arguably the US Navy's AN/SLQ-48(V) Mine Neutralization System (MNS), manufactured by Alliant Techsystems Inc. Using a conventional electro-mechanical cable, the vehicle can reach a speed of 6 kt (11 km/hr), and operate to a depth of 3,281 ft (1,000 m), while carrying two cable cutters (MP-1) and a bomblet (MP-2). It has a high resolution sonar, low light TV and meets stringent military specifications. It is only operated by the US Navy, with 57 vehicles built that operate from the fleet of 14 full ocean MCM (Mine Counter Measure) ships and 12 coastal MHC (Mine Hunter Coastal) ships.



US Navy's Mine Neutralization System

The German Navy uses the battery operated *Pinguin B3*, developed by STN Systemtechnik Nord. Over 30 of these vehicles have been built. They can operate to 656 ft (200 m), have a maximum speed of 8 kt (15 km/hr), and carry a payload of 551 lb (250 kg).

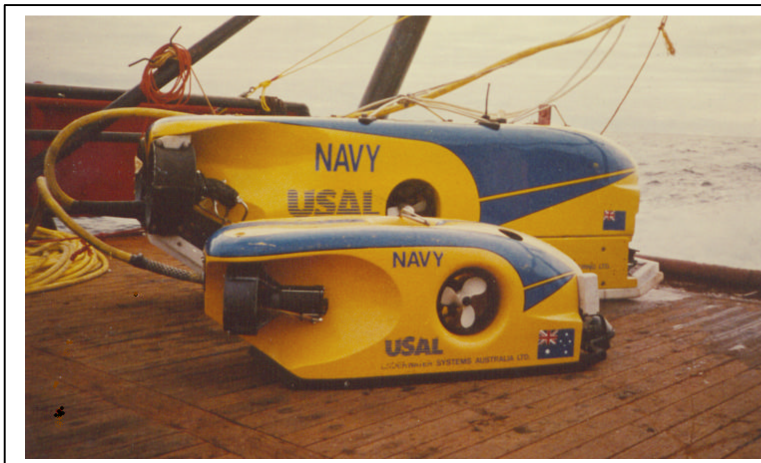
Germany's *Pinguin B3*

Sweden's contribution is the *Double Eagle*, developed by Bofors Underwater Systems AB, SUTEC. It sports a speed of 5 kt (9 km/hr), 984-ft (300-m) operating depth and a 44-lb (20-kg) payload. An interesting control aspect of the *Eagle* series is its ability to operate in any orientation, including upside down. Eight Mk I and 24 Mk II units have been built and are operated by the Swedish and Royal Danish Navies.

SUTEC's Double Eagle

Italy's SMIN Consortium built the *MIN* (Mine Identification and Neutralization).

Canada's contribution, by International Submarine Engineering Ltd., is *the Trail Blazer 25* (right) with a 5.5 kt (10 km/hr) speed, 1,640 ft (500 m) operating depth and 221 lb (100 kg) payload. Two have been built and are operated by Fairey Systems.



Switzerland, landlocked as it is, has provided the *Pluto* and *Pluto Plus* vehicles (see photo to right) developed by Gayrobot-Undersea Technology. The Plus version has a maximum 7 kt (13 km/hr) capability, 984 ft (300 m) operating depth and 176 lb (80 kg) maximum payload. There have been 45 and 22 of the *Pluto* and *Pluto Plus* units developed respectively for various navies.

Other low cost vehicles such as the Benthos Inc.'s *Super SeaROVER* and *MMUROV* vehicles, and Deep Ocean Engineering's *Phantom* vehicles, are marketed in the US as being capable of conducting MCM. There are many others that would fit this category, however, it is not the intent of this publication to provide an exhaustive listing of all systems. Such listings can be found in various references provided in the appendices.

The previous listing of MCM vehicles supports the premise that there exists an adequate capability to locate and neutralize mines. However, it is not an exact science and more often than not the combination of a multitude of mines and Mother Nature's added environmental problems will make their ability to fully clear a mine field limited at best. In the real world, that is as good as can be expected. But, it still does not solve the problem.

Non-Conventional MCM Vehicles

The category of non-conventional MCM vehicles covers two different areas–vehicles launched from submarines and an array of new techniques and devices that are being developed to solve the surf zone environment.

Submarine Launched Vehicles

The future of MCM vehicles in the US Navy will now include submarine launched systems as established in its UUV (Unmanned Undersea Vehicle) Program Plan that identifies clandestine MCM as its top priority. To meet that goal, several systems are planned for development.

The program's first two priorities are the development of the Near-Term Mine Reconnaissance System (NMRS) and the Long-Term Mine Reconnaissance System (LMRS). Together, they are scheduled to nearly reach a $140M combined budget for 1996-2001. Although their name includes the term "reconnaissance" (the next section in this book), their primary application is mine reconnaissance, so they will be discussed in this context. However, if their development is fully successful, mine reconnaissance will probably become only a small portion of their potential.

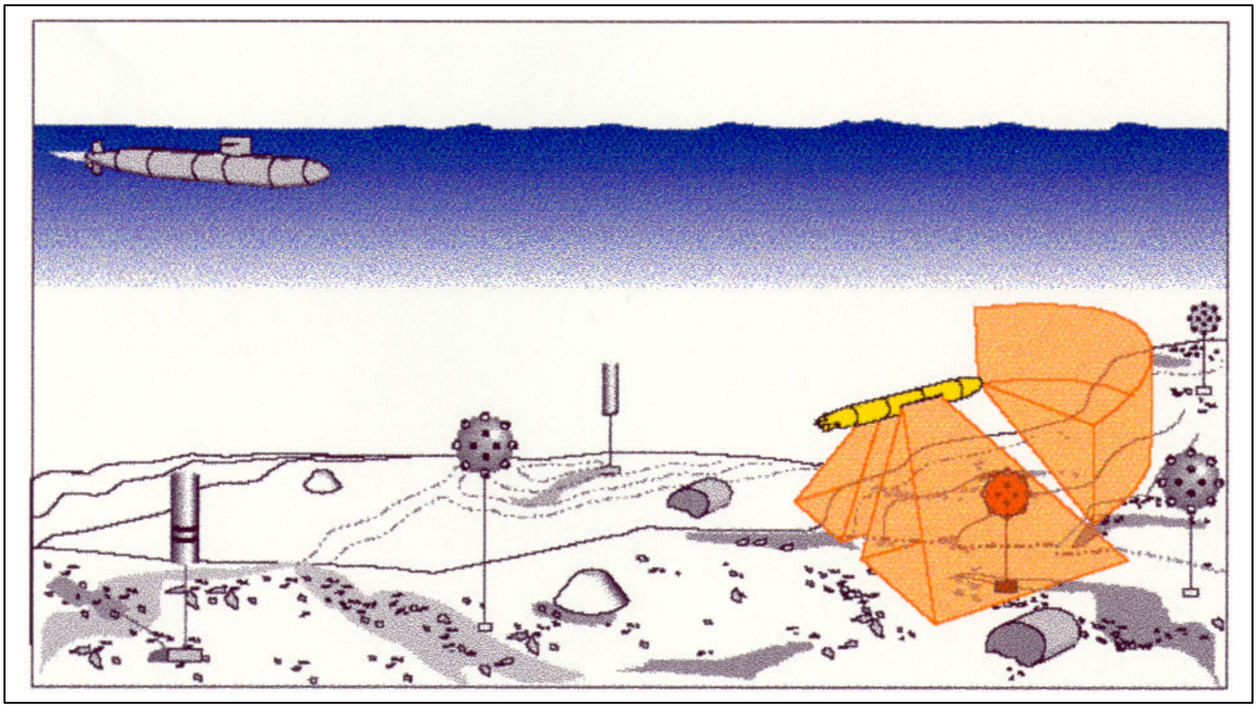
The NMRS contract was awarded to Northrop Grumman Corporation (formerly Westinghouse Corporation's Oceanic Division, Annapolis, MD). The NMRS is based on a previous, little talked about, US Navy program. The system is carried onboard a submarine with the vehicles, operator consoles, tether, winches and other system components housed like torpedoes on the standard storage racks. The vehicle is launched and recovered through the torpedo tube using a drogue that provides a docking point to haul the vehicle back in. The vehicle is battery operated, using silver-oxide batteries and communicates with the mother submarine via a fiber optic cable. The system will have the ability to return to the submarine for autonomous recovery should the communication link be broken. As indicated earlier, the Navy's concern is now in the littoral regions and accordingly, the NMRS will target water depths ranging from 10 to 200 ft (3 to 61 m). The vehicle is 1.8 ft (0.53 m) in diameter and 17 ft (5.2 m) long. Onboard the 2,250-lb (1,020-kg) vehicle will be a sensor suite made up of a forward-looking sonar for detection and classification of MLOs in the water column and a side-looking sonar to handle the bottom targets. The initial operational capability (IOC) of the NMRS is planned for 1998-99.

The LMRS, with an expected contract value worth nearly $400M over the next 20 years, will replace the interim NMRS. The NMRS will fill the need until the production of 6-12 LMRS systems meet a planned IOC of 2003. Unlike the NMRS, the LMRS will be fully autonomous, with either short-range underwater communication with the mother submarine or long range RF communication on the surface. The vehicle concept will remain similar to the NMRS, with a full sensor suite to locate and classify MLOs, but the requirements will be more stringent. The goal of the system is to achieve the following:

- Vehicle Sortie Reach (nautical miles (nm)) 120
- Total System Area Coverage (square nm) 650
- Area Coverage Rate (square nm/day) 50
- Minimum Mine Reconnaissance Water Depth (ft) 40
- Maximum Vehicle Operating Depth (ft) 1500
- Nominal Single Vehicle Endurance (hr) 62

Adding to the complexity of the ambitious LMRS are the requirements of reduction in magnetic and acoustic signatures, high reliability criteria, etc. The development of the LMRS will be a real challenge for the winning contractor.

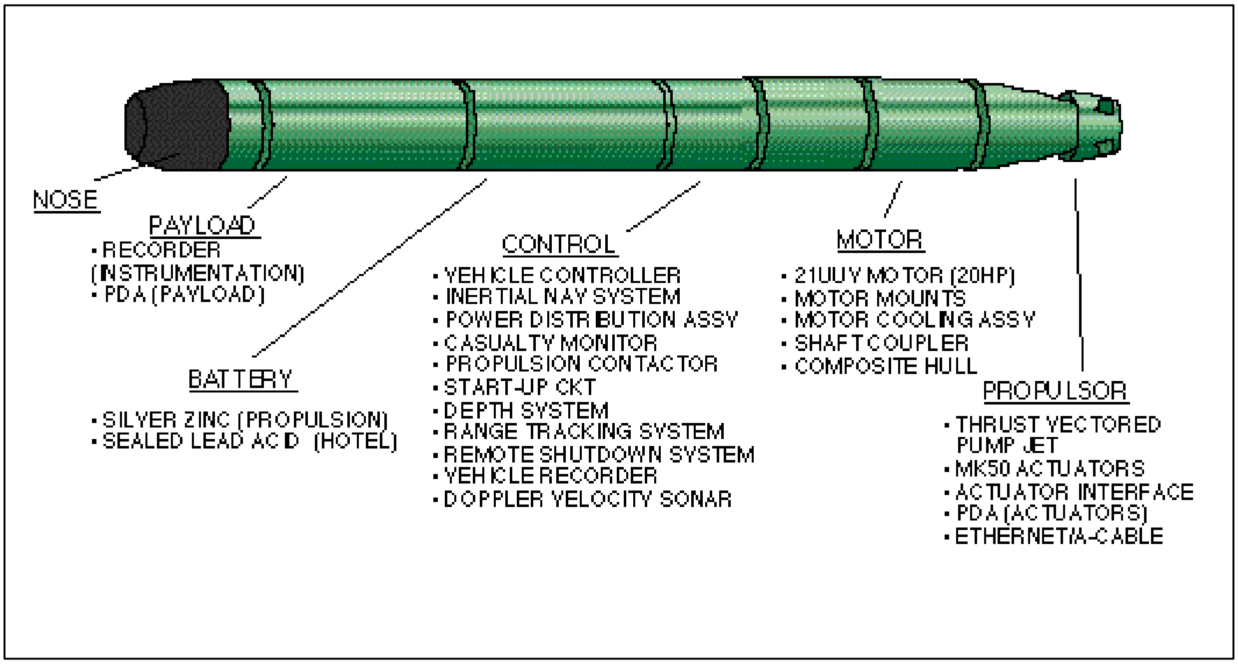
The US Navy is in the two year, second phase of a three phase competitive contractual process to develop the LMRS. The two contractors: Northrop Grumman Corp. and Boeing North America (Boeing acquired Rockwell International Corp., Autonetics and Missile Systems Division, during phase one). The Navy will award the final development contract to the single best contractor at the end of the two year, phase two, detailed design process. The LMRS concept is shown below.



Complimenting the US Navy's clandestine MCM capability from submarines will be a new surface ship system based on the semi-submerged vehicle technology developed by ISE in Canada with their *Dolphin* vehicle. The US Navy has been investigating the use of such vehicles for MCM in programs such as the Remote Minehunting Operational Prototype (RMOP) and has now focused on the Remote Minehunting System (RMS) with an IOC of 2005. The basic concept is to provide over-the-horizon mine reconnaissance using the semi-submerged, diesel powered, ROVs to tow sensors below the surface on a retractable tow cable. This technique underscores the new doctrine of placing the search sensors in front of the ships to locate the mines, instead of driving the ships over the mines while looking for or neutralizing them–not a wise approach considering the capability of modern mines.

In addition to the large scale programs, the US Navy is investing into the development of UUV technology through programs at the Defense Advanced Research Projects Agency, the Office of Naval Research, and various Advanced Technology Demonstrations (ATDs). Work is being performed in the areas of propulsion, system quieting, energy systems, motors, communication systems, command and control and other related subsystems.

Test bed vehicles such as NUWC's (Naval Undersea Warfare Center) Large Diameter UUV (LDUUV), a torpedo shaped, 26.5 in (67 cm) diameter, 25 ft (7.6 m) long test bed, and the planned 21 in (53 cm) diameter UUV (figure below), will provide a platform for the development of technologies required by future Navy MCM systems.

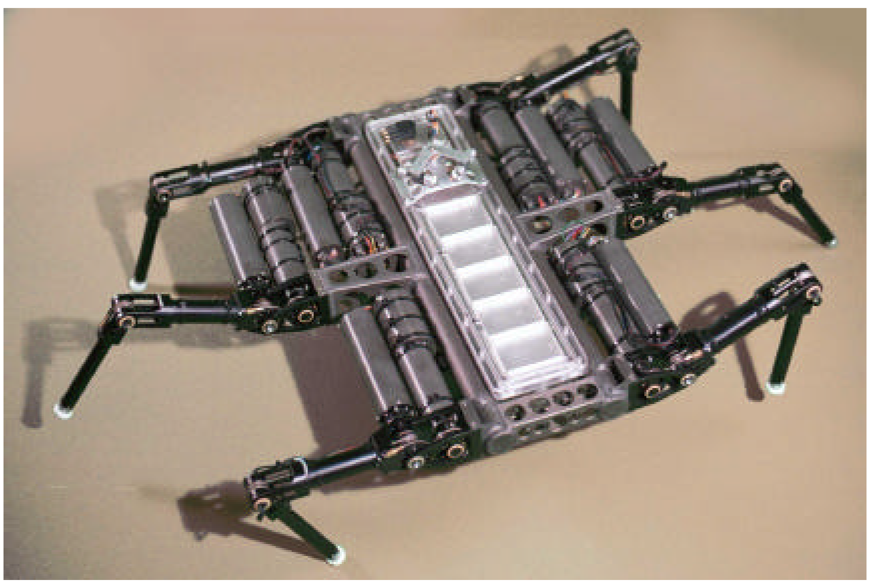


The US is not the only country developing unmanned underwater systems that are adaptable for MCM. The British firm GEC-Marconi has developed a Research Autonomous Underwater Vehicle (below) for the British Department of Trade and Industry's Civil Applications Division. This "multi-use test bed vehicle" is being developed by a collaborative team of Marconi Underwater Systems, Chelsea Instruments, and Moog Controls.

The testbed is based on Marconi’s 21-in (53-cm) heavyweight torpedo. The design includes onboard systems that provide operation to 900-ft (274-m) depths, a speed of 4.4 kt (8.2 km/hr), and can travel for 36 hours with a range of 185 miles (298 km). Although originally developed for oceanographic data acquisition, the MCM mission is one they feel they can meet. This vehicle will be discussed more in the AUV section.

Surf Zone MCM Techniques

As discussed earlier, the surf zone is probably one of the worst on Earth when it comes to performing any type of work. It is difficult to build structures to survive the coastal environment, much less locate and neutralize mines in the "forbidden zone." However, there are on-going programs that are investigating various techniques to neutralize mines in this hazardous zone. Most of them use some type of small ROV or autonomous system, however, there are those that reside near the "lunatic fringe" of the technology–not because of their ability to achieve success, but from their "interesting" approach to the problem. Terms like "robo-lobster" are not uncommon in this field of investigation. Some of the most interesting work is the Autonomous Legged Underwater Vehicle (ALUV) being investigated by IS Robotics and Rockwell International.



The *Ariel* ALUV finding a mine

The ALUVs are crab-like walking robots, not unlike some seen in recent science fiction movies. The intent is to launch these beasties in large numbers into the surf zone, where they will seek out and locate MLOs using various sensors such as touch, magnetic gradiometers, metal detectors, ultrasonics, etc. Once they find an MLO, they will stake out their territory, communicate with the others, and remain until told to destroy the mine with their onboard charges. Vehicles such as *Ariel*, shown above, have been developed and others are planned.

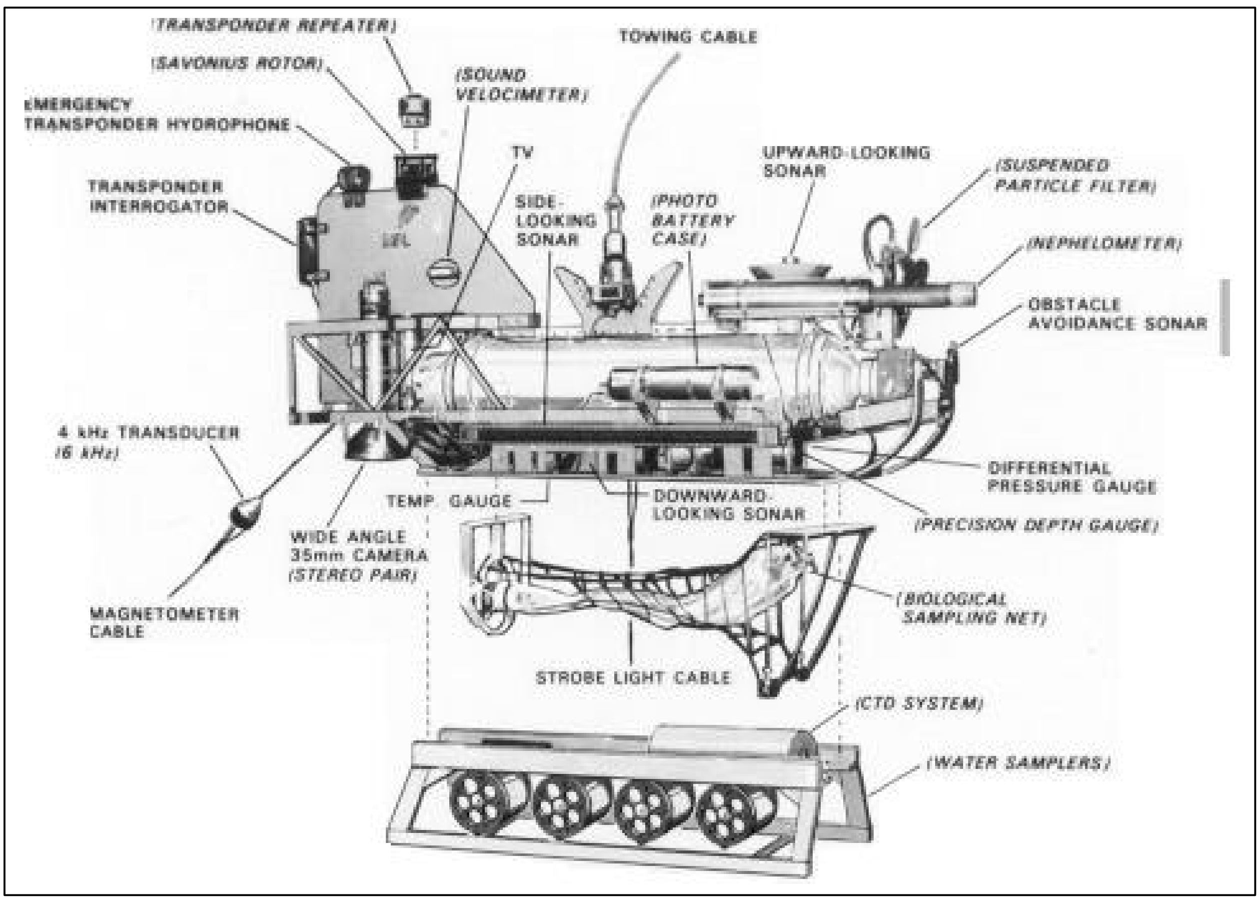
Whether such devices are stressing the limits of technology, or just logical approaches to the problem, they are being developed and demonstrated with rather impressive results. Time will define their level of success, but regardless, they are a tribute to the sophistication and potential of unmanned underwater systems.

Search/Recovery

The search/recovery section on unmanned underwater systems is dominated by government/military development, primarily due to the magnitude of the problem, and the desire for recovery of objects from any ocean depth. The magic number for the operational depth of such systems has always been 20,000 ft (6,096 m), the depth that covers 98 percent of the ocean floor. This topic will be divided into the two categories of search and recovery. Search primarily involves semi-autonomous vehicles and towed systems while recovery requires tethered ROVs.

Search

Underwater search has traditionally involved towed systems. These vehicles, such as Deep Tow (shown below)–one of the first such systems–carry the necessary sonars, photographic equipment and other sensors required to locate everything from lost torpedoes to entire aircraft.

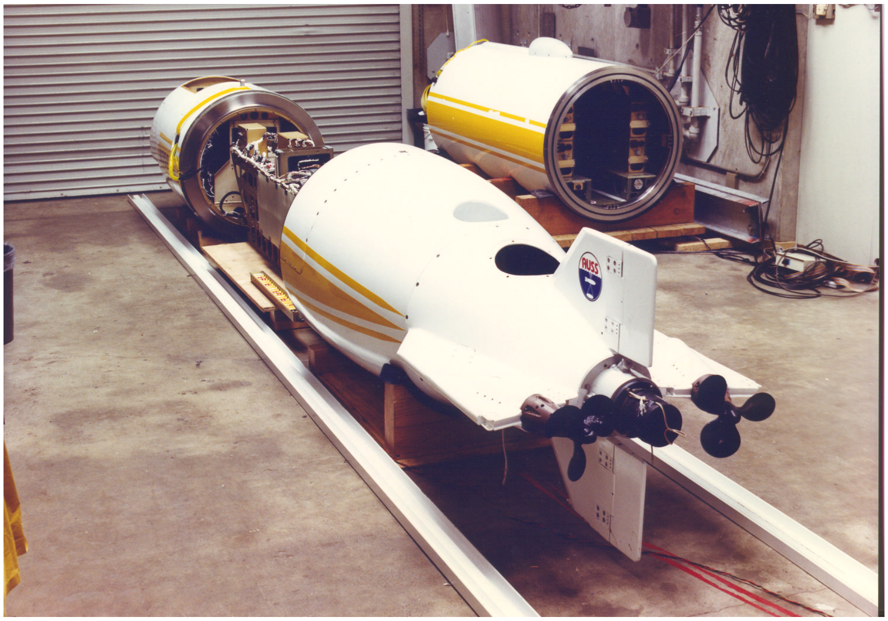


The primary method of operation is to lower the usually very heavy system into the water with a crane and then tow it at the desired depth by varying the length of the strong electromechanical cable. Whereas Kevlar has provided the breakthrough for long length cables for free flying ROVs, where the tether needs to remain essentially neutral in the water column, steel cables are quite acceptable for towed systems. Modern cables now include fiber optic communications that provide excellent bandwidth for multiple sensor transmission. It should be noted that most of the initial towed systems were developed for oceanographic investigations at institutions such as the Marine Physical Laboratory (MPL) of Scripps Institution of Oceanography (SIO) and Woods Hole Oceanographic Institution (WHOI), and were in most cases backed by government or Navy funding. As the technology became more advanced, commercial systems could be procured by the government and operated by contractors under government funding. Today, there are few systems in the US operated directly by the government, however, other countries, especially Russia, have many that are believed to be government backed/operated systems. Examples of several of these systems, most capable of 20,000 ft (6,096 m) or more, are provided in the table at the end of the History section.

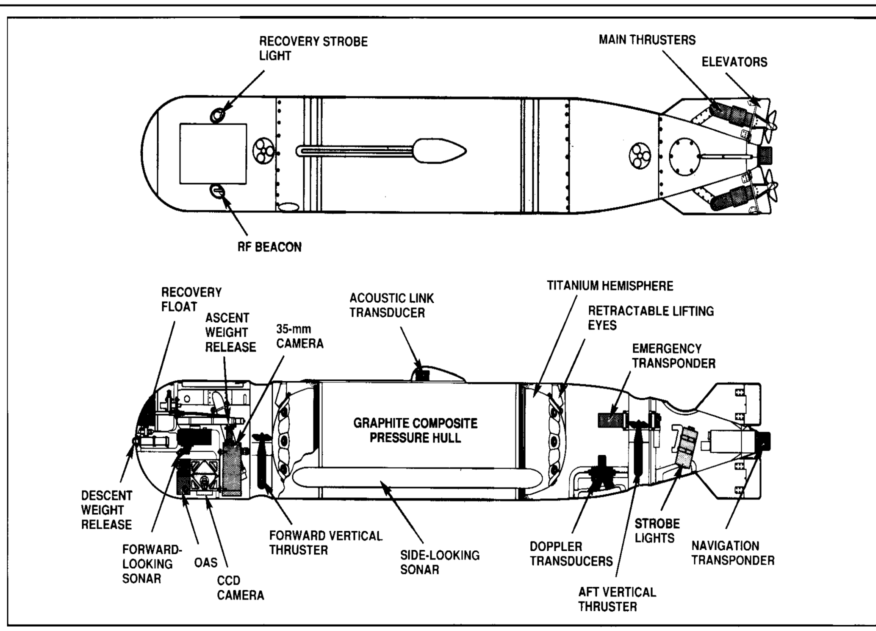
The towed systems have proven their worth many times over, however, to their detriment, they are inefficient if taken in the context of today's technology. On the plus side is their ability to carry large sensor suites that are operated with unlimited power duration because of the tow cable. On the negative side is the requirement to turn the ship each time another pass over the search area is required. For a 20,000-ft (6,096-m) system, the time to bring the vehicle back on the proper track is extremely high, especially when compared to the time that the vehicle is actually on track searching. Studies have shown that the search time can be reduced by an order of magnitude if the cable is eliminated and a semi-autonomous vehicle used. The French and the US Navy followed this approach when they decided to develop the *EPAULARD* and the Advanced Unmanned Search System (*AUSS*), respectively.

The *AUSS* vehicle is a battery operated search system that can run autonomous search patterns to depths of 20,000 ft (6,096 m) and send the data it acquires back to the mother ship acoustically. The vehicle follows a pre-programmed track, searching with its side scan sonars until a target is located. At that time, it closes on the target until it is acquired in the forward look sonar, and then with the TV camera. High resolution photographs are sent to the surface operators via the acoustic communication link where determination of additional search requirements can be made. After the object has been investigated, the vehicle will automatically return to the point on the search track where it left off and continue the search.

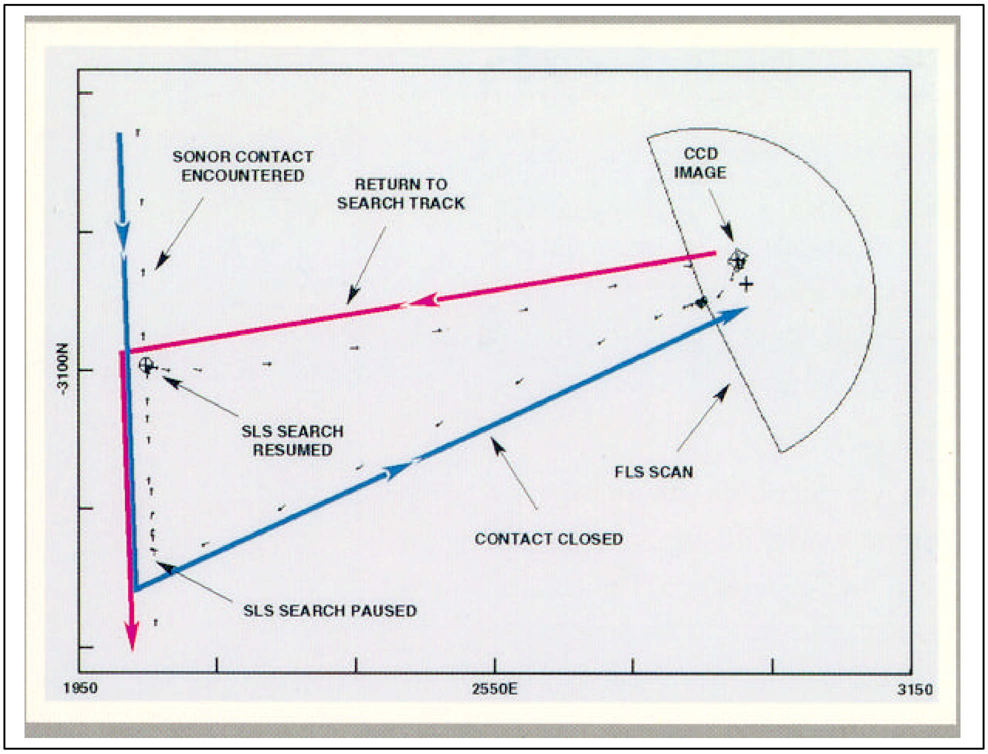
The following series of figures provides an overview of the techniques and capabilities of such semi-autonomous search technology. The *AUSS* is operated by the Space and Naval Warfare Systems Center, San Diego, CA (SSC SD) where it was developed.



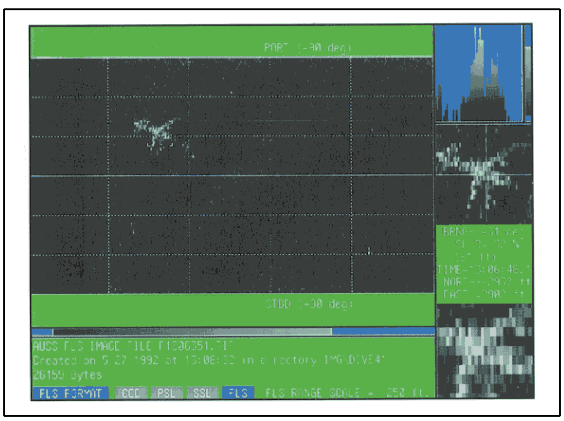
***AUSS* with GRP hull section removed**

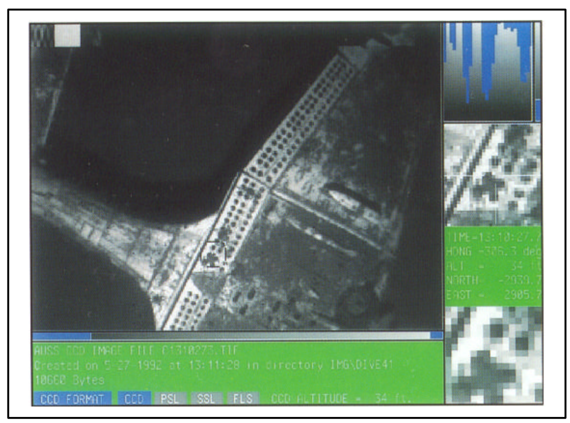


***AUSS* vehicle components**



Plot of 14-minute contact evaluation.





Sonar contact of plane
(acoustic transmission)

Photograph of plane
(acoustic transmission)

Concurrent with the development of the *AUSS* technology in the US, Russia (at that time the ROV leader in the Soviet Union) was secretly developing its own line of military search systems. Some references indicate that the developments may have been ongoing in the early 1970s. Several were developed at the Institute of Marine

Technology Problems (IMTP) in Vladivostok, the most noteworthy being the *MT-88* vehicle, also known as the *Sea Lion*. This vehicle conducted a side-scan and photographic survey of the *Yankee*-class ballistic missile submarine that sank off Bermuda in 1986. Forty-five dives below 18,000 ft (5,486 m) were made in the search zone, producing over 40,000 photographs. In addition, the Soviet *Mike*-class attack submarine that sank off Norway in April 1989 in 6,500 ft (1,981 m) of water was surveyed during 17 dives with a total of 1,000 photographs taken of the wreckage. It is obvious that the Russian AUV fleet has been very active operationally.

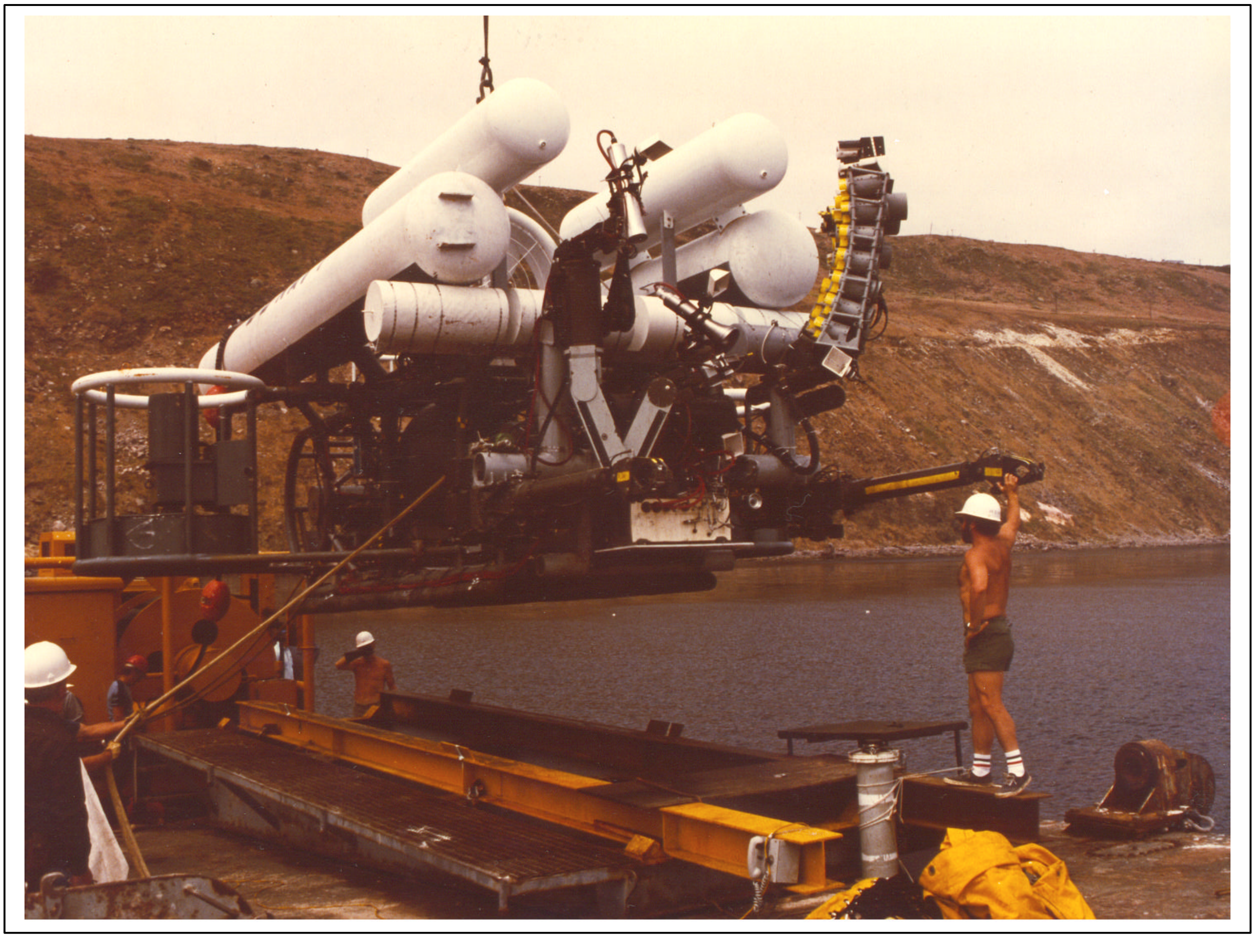
Recovery

The reason that one searches for an object is generally a desire to work on or recover it. In the military case, it is usually the latter. More and more military aircraft are falling into the world's oceans, often with classified payloads or nuclear weapons. When that happens, the military, both in the US and other countries, has a significant desire to recover the wreckage, or at least the critical portions of it. To provide that ocean-wide capability, the military developed the technology base to support the fielding of full ocean depth, 20,000 ft (6,096 m) capable ROVs.

Several programs in the US Navy have addressed deep ocean recovery technology. Assuming the vehicles are available to reach the deepest ocean realms, the tools and techniques to recover lost items from such depths also had to be addressed. One program that considered such techniques was the Deep Ocean Recovery System (DORS) program, which was conducted at the SPAWAR Systems Center, San Diego (at that time–NOSC), California.

The objective of the program was to develop the technology to allow recovery of items from the ocean floor that ranged from flat plates and large structures up to jet engines and entire aircraft. The vehicle used was a 22 ft (6.7 m) long ROV–essentially an underwater tugboat–the Pontoon Implacement Vehicle (PIV). The PIV was developed as part of the Navy's Large Object Salvage System (LOSS) program, a 1970s era program that used gigantic pontoons to recover entire submarines intact from the ocean bottom. The pontoons, each capable of lifting 100 tons, were placed onto the submarine by the PIV, which maneuvered the massive cargo using its 4 ft (1.2 m) thrusters. Once in place on the submarine, the pontoons were attached and dewatered using a liquid nitrogen buoyancy generation system.

Attached to the PIV was the Navy's Work System Package (WSP), which was a multi-manipulator work system that had the capability to exchange various hydraulic tools underwater such as cable cutters, drills, spreaders, jacks, stud guns, etc. The tools were handled with the primary work manipulator while two strong grabbers restrained and oriented the work system. Two SIT TV cameras were available to provide dual perspectives of the work site. The WSP/PIV system is shown during testing off the California coast at San Clemente Island in the figure on the next page. The successful testing of the WSP/PIV resulted in the rigging and recovery of an intact F4 aircraft using a computer controlled lift module.



R. Wernli (right) directs the launch of the US Navy's WSP/PIV

There are several shallower water capable systems that can be used for recovery, as shown in the table on the following page, however, only two military owned systems are capable of 20,000 ft (6,096 m) operation: *CURV III* and *ATV*.

The *CURV III* (Cable-controlled Underwater Recovery Vehicle) was originally developed by the US Navy as an ordnance recovery tool for use on the Navy's sea test ranges. It reached a capability of 10,000 ft (3,048 m) while being developed and operated by NRaD (now SSC SD) prior to going into storage. It was soon resurrected by the Supervisor of Salvage and under their direction, upgraded to a 20,000-ft (6,096-m) capability under a contract with Oceaneering Technologies Inc. (at that time Eastport International). Concurrently, the *ATV* (Advanced Tethered Vehicle) was being developed by NRaD to provide the Submarine Development Group One in San Diego (now the Submarine Development Squadron Five – SUBDEVRON5) with a 20,000 ft (6,096 m) system. Interestingly, both systems reached the magic 20,000-ft (6,096-m) barrier within one week of each other–the *CURV III* first for a 20,105-ft (6,128-m) record and the ATV second, setting a 20,600-ft (6,279-m) record.

ROVs WITH GREATER THAN 10,000-FOOT CAPABILITY

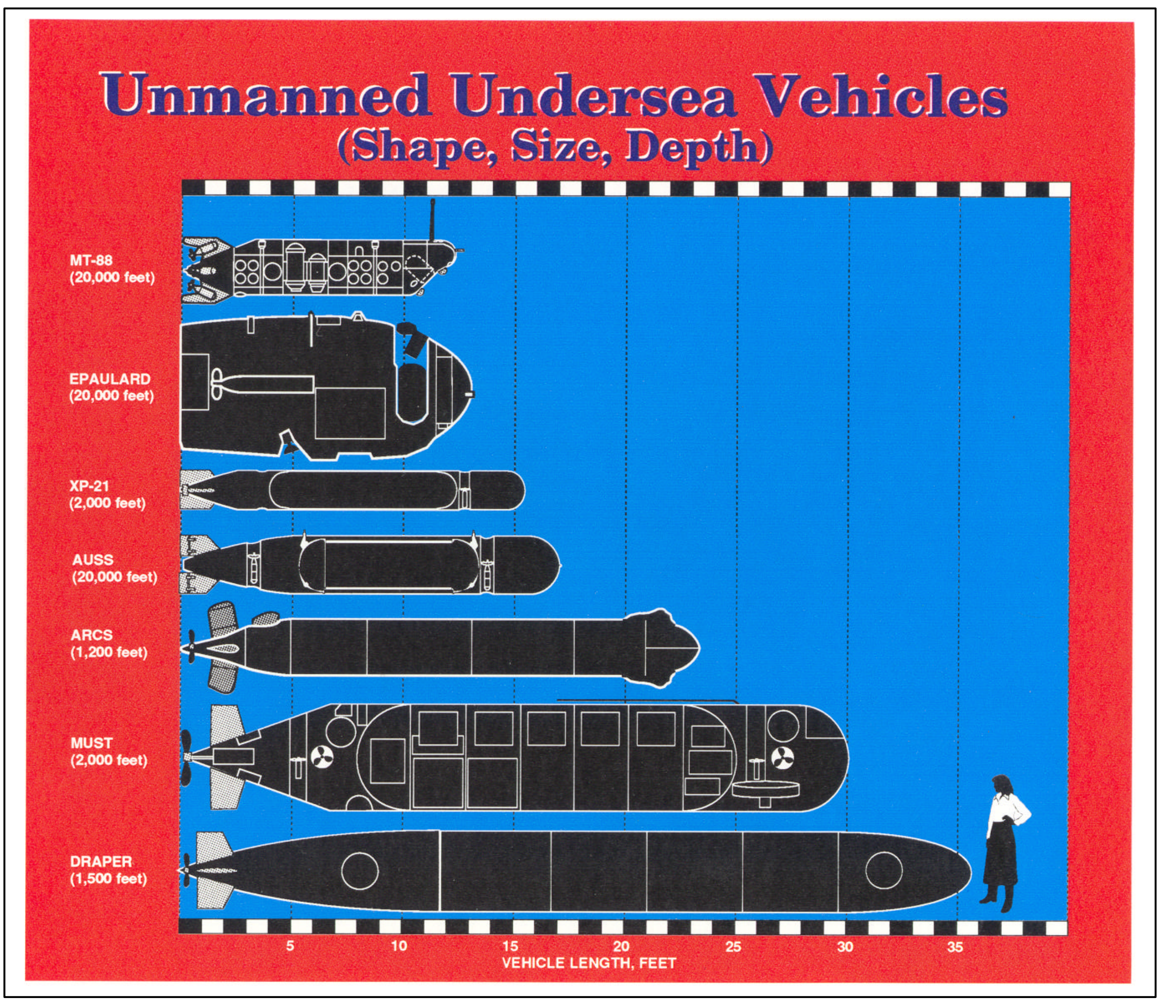
VEHICLE	DEVELOPER	DESIGN DEPTH	MAX DEPTH ACHIEVED
KAIKO	MITSUI/MITSUBISHI/ KAWASAKI/JAMSTEC, JAPAN	36,089 FT	35,791 FT (MARIANA TRENCH)
ATV	SPAWARSYSCEN, SAN DIEGO, CA., U.S.	20,000 FT	20,600 FT (PACIFIC)
CURV III	OCEANEERING TECH- NOLOGIES INC., U.S.	20,000 FT	20,105 FT (PUERTO RICAN TRENCH)
MAGELLAN 825	OCEANEERING TECH- NOLOGIES INC., U.S.	26,000 FT	20,000 FT (PUERTO RICAN TRENCH)
MAGELLAN 725	OCEANEERING TECH- NOLOGIES INC., U.S.	25,000 FT	17,800 FT
MAGELLAN 680	OCEANEERING TECH- NOLOGIES INC., U.S.	20,000 FT	COMMERCIAL VERSION OF CURV, NONE BUILT
GEMINI	OCEANEERING TECH- NOLOGIES INC., U.S.	20,000 FT	14,800 (AIRCRAFT RECOVERY)
JASON/MEDEA	WOODS HOLE OCEAN- OGRAPHIC INST., U.S.	20,000 FT	13,000 FT
HYSUB 5000	INTERNATIONAL SUB- MARINE ENGINEERING, CANADA	16,400 FT	15,088 FT
DOLPHIN 3K	MITSUI/JAMSTEC, JAPAN	11,247 FT	11,247 FT (SIKOKO BASIN)
TIBURON	MBARI	13,124 FT	
VENTANA	MBARI	13,124 FT	
TRITON	PERRY TRITEC, U.S.	20,000 FT	DESIGNED ONLY
ROV 6000	IFREMER, FRANCE	20,000 FT	UNDER DEVELOPMENT
VICTOR 6000	IFREMER, FRANCE	20,000 FT	

The ATV and the CURV III may have broken the 20,000-ft (6,096-m) barrier, however, both of these records were shattered in 1995 when Japan's *Kaiko* dove to the bottom of the Mariana Trench setting a tethered vehicle depth record that may be equaled, but never surpassed–35,791 ft (10,909 m).

The deep ocean recovery capability that exists in the US Navy supports recovery operations to depths of 20,000 ft (6,096 m), either through the use of vehicles operated out of SUBDEVRON5 or through those Navy owned vehicles operated under contract by companies such as Oceaneering Technologies, Inc. They may not raise the *Titanic*, but they can get most missions accomplished. And, as shown by the examples provided in Object Location and Recovery earlier in this chapter, existing commercial assets can be called in when necessary to support most conceivable recovery operations.

Intelligence, Surveillance and Reconnaissance

The world military outlook has moved from the deep ocean to the near shore environment because of the end of the cold war and the emergence of conflicts with smaller nations. This new doctrine is driven by quick response, and with that comes the



age of information warfare–ISR (intelligence, surveillance, and reconnaissance). Whether it is reconnaissance to help with the egress of submarines from their home ports or to watch others, the goal is to perform it covertly, and that provides the opening for unmanned underwater systems. Just as space satellites perform this task from above the ocean, unmanned systems can play the role of ocean satellites and perform it silently from below–an innerspace satellite. The good news is that the potential is there, however, it is costly to implement when compared to existing ocean budgets, but inexpensive when compared to the cost of outer space satellites. Major defense organizations and contractors have put money into the development of testbeds to address these military missions (see figure, previous page). Those testbeds, along with some of their accomplishments, are discussed below.

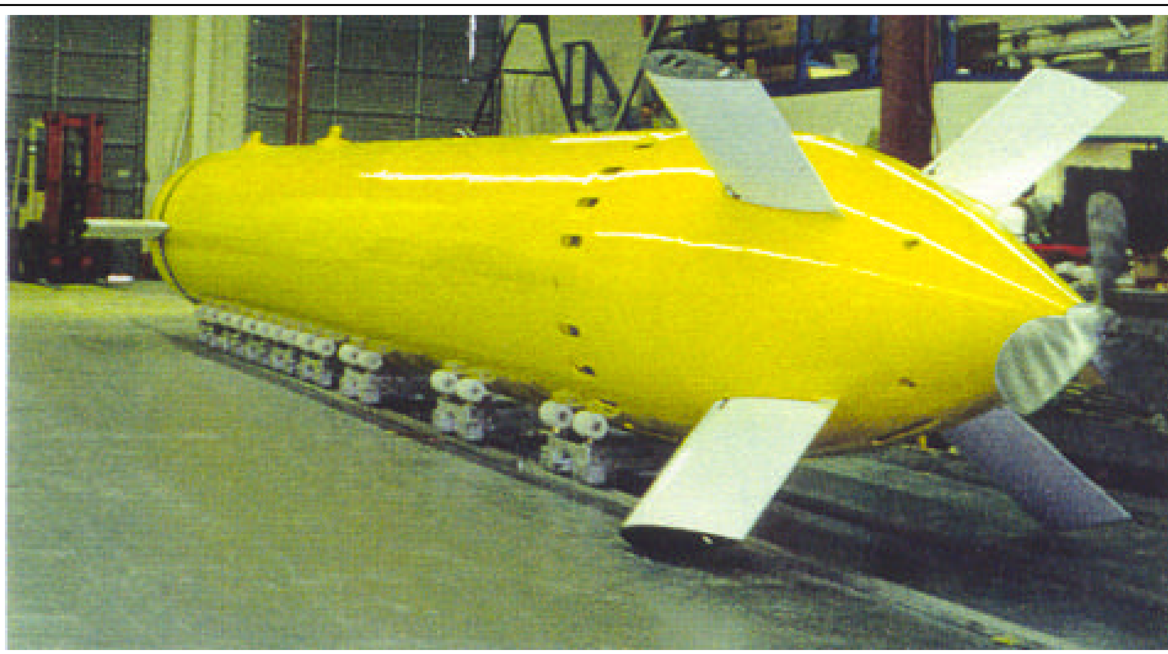
The "Innerspace Shuttles"

One of the overriding premises of ISR is that to perform such a mission, the vehicle will need to either transit large distances, carry a large payload, stay for an extended period, or all of the above. Those drivers, along with the fact that most technologies will be proven in less efficient packaging schemes to save developmental funding, force the developers to larger vehicles. The largest testbed vehicles in the world are presently developed by Canada and the US; the *Theseus* (Canada) and the *MUST* and DARPA *UUV*s (US). These behemoths, 35 ft (10.7 m) long by 4.2 ft (1.3 m) in diameter; 35 ft (10.7 m) long–the baseline design is 30 ft (9.1 m)–by 4.5 ft (1.4 m) in diameter; and 36 ft (11 m) long by 3.7 ft (1.1 m) in diameter, respectively, are described below.

Theseus (Canada)

The *Theseus* vehicle was developed by ISE Research Ltd., under sponsorship of the Canadian Department of National Defence. It began development in 1992 and performed operational demonstrations of its primary mission in 1996–to lay underwater fiber optic cables for connection to surveillance arrays. The cable deployment project was a joint US/Canadian venture, called Project Spinnaker, to develop and demonstrate lightweight, low-power, low-cost acoustic arrays under the arctic ice.

The *Theseus* vehicle, shown below, displaces 19,000 lb (8,617 kg), can reach a depth of 3,280 ft (1,000 m), has a range of 250 miles (400 km) and a speed of 4 knots (7.4 km/hr). It operates on 274 kWh Silver Zinc batteries. The pressure hull is 7075 aluminum and the free flooded sections are GRP.



The mission of Project Spinnaker was to place a large-aperture acoustic array beneath the arctic ice pack in the Lincoln Sea. The *Theseus* AUV was used to deploy a fiber optic cable from shore to the underwater connection site 109 miles (175 km) distant under the ice. It was launched through a 6.6- by 42.6-ft (2.0- by 13-m) hole cut through the ice.

Theseus uses a Honeywell MAPS 726 inertial navigation unit, an EDO 3050 doppler sonar and a low frequency system for acoustic homing on a target. Obstacle avoidance is performed with a Sonatech STA-031-1 forward-looking sonar. The combined system provides a navigational accuracy of approximately one-percent of distance traveled. The vehicle also received periodic position updates from acoustic beacons lowered through ice holes at six different locations.

Upon arriving at the site, the vehicle flew through a "catcher" loop suspended below the 8.9 ft (2.7 m) thick ice, which allowed the fiber to be retrieved to the surface where it could be spliced to the array fiber completing the connection to shore. *Theseus* then returned to the launch site where an ROV was used to assist in the vehicle recovery. A total mission length of 216 miles (350 km) was achieved; energy used was 149 kWh. The vehicle demonstrated a navigational error of less than 0.5 percent of the distance traveled with cross-track error reducible to 0.05 percent.

MUST (US)

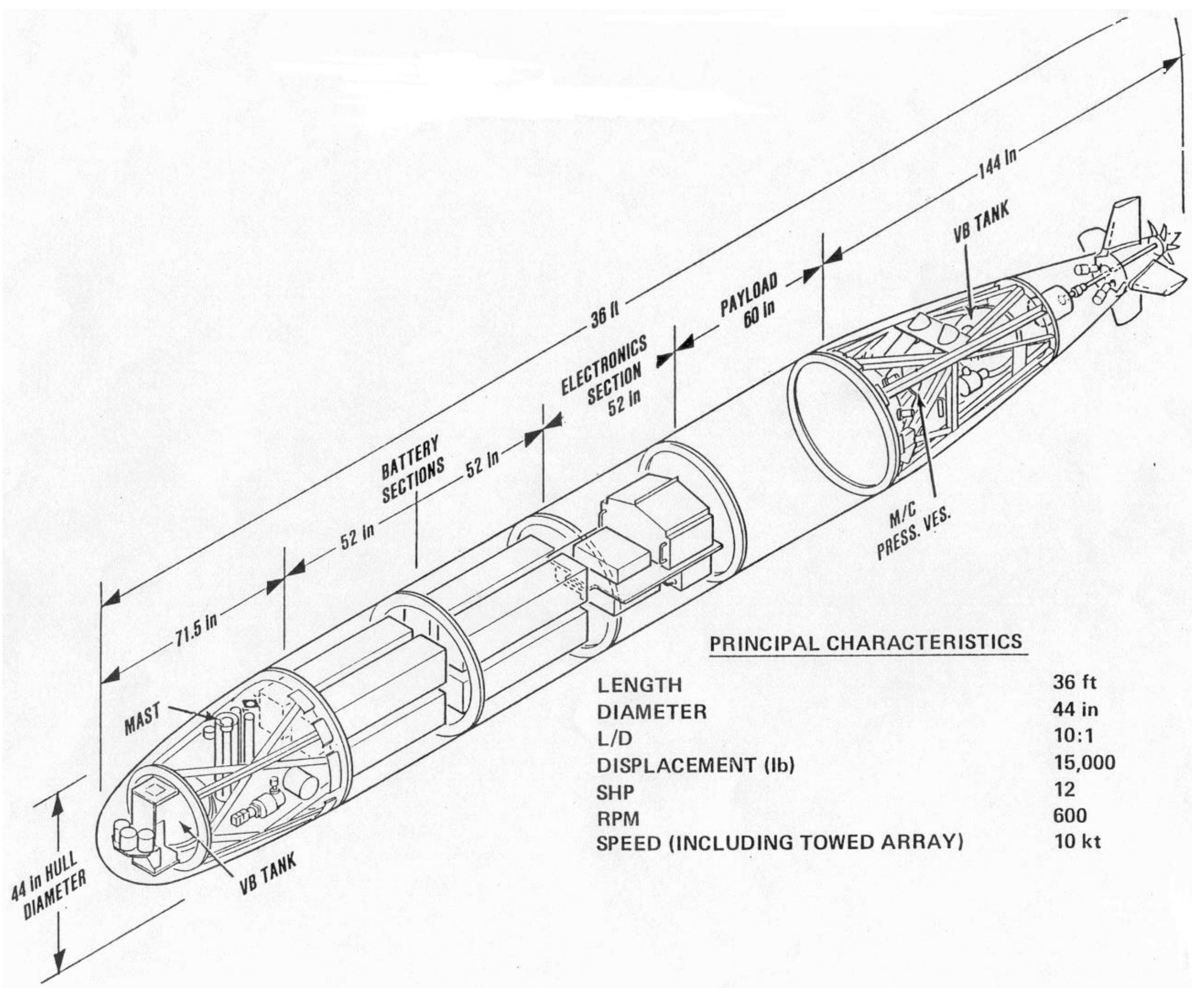
The *MUST* vehicle (Mobile Undersea Systems Test Laboratory) was developed originally by Applied Remote Technology (prior to their acquisition by Raytheon) for Martin Marietta Corporation. Subsequently, the vehicle has been operated by Perry Technologies, which is an operating unit of the Lockheed Martin Corp. (Martin Marietta and Lockheed merged in 1996). The vehicle was developed to provide a large, easily configured testbed, primarily for military missions such as anti-submarine warfare (ASW), or other AUV missions.

The large diameter allows the use of rack mounted electronics, which helps keep the cost of subsystem development down. It has a capability of 53 cubic feet (1.5 cubic meter) of dry payload electronics in the baseline system with a maximum hotel power load of 7.5 kW. The vehicle has a 2,000-ft (610-m) depth capability, and can achieve a maximum range of approximately 100 miles (161 km) at 4.5 knots (8.3 km/hr). It carries up to 100 automotive lead acid batteries within its 6061-T6 aluminum structure.

DARPA UUV (US)

One of the most ambitious programs in the US was DARPA's Unmanned Undersea Vehicle program. DARPA contracted to Charles Stark Draper Laboratory, Inc., in 1988 to develop two "rapid prototype" UUVs (the term adopted by the US military) for an initial award of nearly $24 million.

The Navy's *UUV* – developed by the Charles Stark Draper Laboratory, Inc.



The vehicle weighs 15,000 lb (6,803 kg) in air, can be operated to a depth of 1,500 ft (457 m) and has an endurance of 24 hours at 10 knots (18.5 km/hr). It has the capability to communicate via RF, underwater acoustics or optical fiber cables.

Navigation is provided by a correlation velocity log and a doppler sonar. It uses silver zinc batteries with a rated capacity of 325 kWh. The structure uses a high cost rib-stiffened titanium pressure hull, in multiple sections, with a fiberglass fairing. The hull was designed to provide a 5 ft (1.5 m) long payload volume for the demonstration of various mission packages. These mission packages included the following.

The first primary mission the vehicles investigated, which was a classified mission, was the TAS (Tactical Acoustic System), with the payload provided by Martin Marietta Aero and Naval Systems.

The second mission addressed communication technologies, which were accomplished by the vehicle using a laser communication system. This was demonstrated between the UUV and the *USS DOLPHIN* submarine off San Clemente Island, California in 52-ft (16-m) attenuation length water. The maximum data transmission rate achieved was 100 Mbps at a range of 250 ft (76 m) while transiting at 2.5 knots (4.6 km/hr).

The third demonstration was the Mine Search System (MSS) with the payload developed by Lockheed Missiles and Space Corporation, which included a mission controller, fiber optic tether and tether management system. The goal was accurate reconnaissance and penetration of a suspected minefield and/or safe guidance of a submarine through a minefield while under semi-autonomous control. The MSS configured UUV successfully conducted the semi-autonomous minefield survey and transferred the data to the host via radio from a rendezvous point.

The final mission was the Autonomous Minehunting and Mapping Technologies (AMMT) program. Technologies included a government supplied forward looking and side looking sonar system developed by the University of Texas, Applied Research Laboratory (ARL:UT). Lockheed Martin Tactical Defense Systems (formerly LORAL) provided the navigation suite–a doppler-aided with enhanced Kalman filtering. The acoustic communication system was provided by Woods Hole Oceanographic Institution. Imaging systems used included a laser line scanner developed by Applied Remote Technology (purchased by Raytheon) and a CCD camera.

Other technologies investigated under the DARPA program included fuel cells and magnetic communications. For the fuel cell program, LORAL and International Fuel Cell were funded by DARDA to develop two fuel cell concepts for demonstration in the *UUV*. The fuel cell power systems were required to produce 1 MWh of net energy for up to three weeks continuous operation. LORAL was awarded an $8.3 million contract to develop an Aluminum-Oxygen fuel cell that would have an energy density of 3-5 times that of silver zinc batteries, with a goal of increasing the performance by 10 times. International Fuel Cells were investigating a proton exchange membrane (PEM) fuel cell system. Results of the fuel cell studies will not be addressed herein.

The "Missiles"

If the previous systems can be likened to "space shuttles," then the smaller, torpedo sized systems are more akin to "missiles"–their smaller size limiting their endurance, but not their impact on potential missions. Several systems have been investigated by the US Navy including the 21 in (53 cm) diameter Freeswimmer vehicle at SSC San Diego and the Large-Diameter UUV (LDUUV) and small diameter UUV at the Naval Undersea Warfare Center. These vehicles, and others such as the NMRS and LMRS systems, are discussed in Chapter 1.

One of the successful “torpedo sized” vehicles was the *XP-21*, developed by Applied Remote Technology (ART)–see photo, Chapter 1. Much of the *XP-21*’s design was based on technology gained when ART developed the MUST system for Martin Marietta. The difference is that the *XP-21* is a 21 in (53 cm) diameter vehicle as opposed to the 54 in (137 cm) diameter MUST. The goal was to provide a torpedo sized test platform for advanced sensors, communication techniques and other various payloads, and for tactical investigations.

The vehicle is 16 ft (4.9 m) long, extendible to 20 ft (6.1 m), weighs 1,200 lb (544 kg), and can reach a depth of 2,000 ft (610 m). Although the vehicle represents a more realistic mission sized vehicle, it has the usual limitations of a small payload: only 2 cubic feet (0.06 cubic meter) and 250 lb (113 kg)–4 cubic feet (0.12 cubic meter) and 450 lb (204 kg) extended. It can operate for approximately 9 hours at 3.5 knots (6.5 km/hr) with a 300-watt hotel power load.

Demonstrations performed by the vehicle have included deployment of fiber optic micro-cables for the Navy and a successful demonstration of an integrated laser line scanning system.

Intruder Detection

The SPAWAR Systems Center, San Diego, in addition to developing advanced ROV systems, has been heavily involved in waterside security. Various in air and underwater technologies have been integrated to ensure security around Navy installations. One program conducted at the center investigated the use of ROVs to support this mission. The Underwater Security Vehicle (USV) program was required to demonstrate the feasibility of using ROVs to assess designated diver contacts in the near-shore environment. The demonstration system used a *Super SeaROVER* vehicle equipped with a Smiths Hi-Scan 600 sonar. The successful demonstrations proved that an adequately outfitted ROV could acquire, track and intercept diver targets.

ACADEMIC/SCIENTIFIC APPLICATIONS

Technology has taken deep-sea researchers far into the depths since the early expeditions of the H.M.S. Challenger during the 1870s, when the first comprehensive samples of life in the deep ocean were collected. Today, there are several methods to obtain data on benthic communities–from trawls to manned submersibles and unmanned undersea vehicles. Although trawls have their benefits, according to Barry and Baxter in their paper *Survey Design Considerations for Deep-Sea Benthic Communities Using ROVs (MTS Journal*, Winter 1992-1993), they don't provide the real time *in situ* observations available by the other methods. The technological sophistication of ROVs and camera sleds has allowed the biology and ecology of deep-sea habitats and organisms to be efficiently studied.

The problem that exists is the ocean is vast, and the systems used can only spend a limited time in the area, so ecologists rely on quantitative estimates of density, size, or other attributes to investigate the areas of concern. Many scientists still prefer the manned submersibles, however, they are becoming more rare, with existing systems, such as the US Navy's *Sea Cliff* and *Turtle*, being taken off line due to funding constraints. Thus, unmanned undersea systems will provide the primary means of obtaining such deep-sea knowledge in the future. Their ability to obtain high quality photographic and video documentation of the dive site will allow them to reach previously unobtainable locations. In particular, they will provide the scientist with access to populations in rugged terrain, a topography where even the age old trawl is useless.

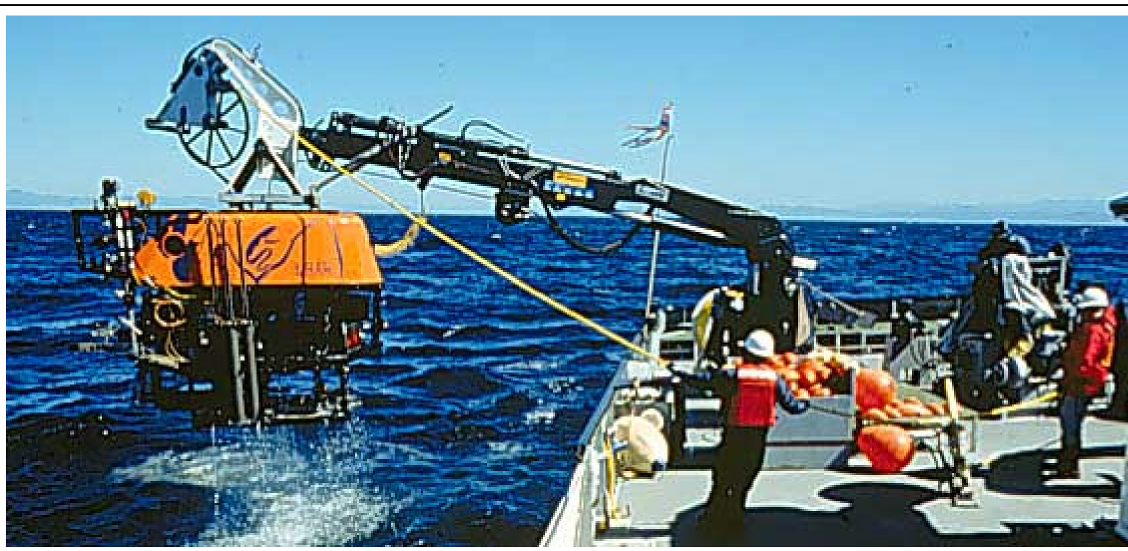
Unfortunately, the use of ROVs and AUVs for scientific research was rather limited in the earlier days of vehicle development, primarily due to the cost of the systems. Also, the inertia of a generation of scientists that wanted to physically be on site either in dive gear or manned submersibles, initially delayed the introduction of such advanced systems into the research arsenal. It wasn't until the development of the first LCROVs that equipment existed for researchers that allowed them to remain topside, while their eyes and ears were sent into the depths. With vehicles priced as low as $10,000, the potential was there, even if rather limited in capability. However, in more recent years, funding has come from a variety of sources, even if limited, and over time unmanned underwater systems have come on line. Today, with the power of advanced computers, AUV testbeds are being developed at many major universities where they provide not only a means for advanced system development, but operational platforms for real world scientific investigations. This section will address the capabilities and advancements in the area of academic/scientific applications of unmanned undersea systems and provide information on resources, institutions and societies that are involved.

On-Going Programs

The MBARI Approach

Background

Underwater vehicles are essential elements in modern oceanographic research, as discussed by Newman and Robison in their paper *Developing a Dedicated ROV for Ocean Science (MTS Journal*, Winter 1992-1993). According to the authors, manned deep submersibles, which have dominated the field in the last two decades, are being joined by ROVs. Most of these ROVs are based on industrial systems, adapted to scientific missions. Such vehicles are often criticized by the users of manned submersibles as awkward, noisy, destructive to the site under study, and inadequate in their data gathering and payload capabilities. A few ROV systems are presently performing deep ocean science missions for the oceanographic community. Most of these are based on adaptations of oil field ROVs, like MBARI's first ROV, *Ventana*, a *Hysub* system built by International Submarine Engineering (ISE) (described later in this section). The Canadian Institute of Ocean Sciences operates a 16,404 ft (5,000-m) *Hysub*, which has been used in geological studies on the Juan de Fuca Ridge. Harbor Branch Oceanographic Institution operated another *Hysub* for several years but has given it up in favor of the Institution's manned submersibles and a new set of ROVs (see later section on HBOI). The University of Hawaii, Hawaii Undersea Research Laboratory, is in the process of adapting an older vehicle, a HydroProducts *RCV 150*, to deep operation in support of oceanographic research, as well as for emergency recovery of the Laboratory's *Pisces V* manned submersible. Other institutions have utilized smaller ROVs (e.g. *Phantom* and *MiniRover* series) for studies generally down to 1,083 ft (330 m).



MBARI's ROV *Ventana* being launched from the R/V *Point Lobos*
(T. Craig Dawe for MBARI © 1997)

MBARI's *Ventana* vehicle (see picture previous page) has been successfully conducting a variety of scientific investigations in and near the Monterey Submarine Canyon since 1988. Operating on a daily basis from Moss Landing, California, to depths as great as 4,790 ft (1,460 m), *Ventana* has logged over 7,000 hours and 1,470 dives. *Ventana* is a *Hysub* ATP-40 with upgraded cameras, sensors, sampling gear and telemetry. *Ventana* preserves most of the reliability and ruggedness typical of hydraulic ROVs, but lacks the quiet operation and the fine control capabilities of more advanced ROVs, particularly those with electric thrusters.

The first deep ROV in the United States designed from the outset to support oceanographic science missions is the Woods Hope Oceanographic Institution's *Jason* vehicle. This 19,685 ft (6,000-m) system has completed science missions that include surveying a deep dumpsite and geological surveys at hydrothermal vent sites on the Juan de Fuca Ridge. *Jason* uses electric motors for its thrusters, pan/tilt, and manipulator, thus avoiding the need for a noisy and less efficient hydraulic power system and providing more precise control capabilities. Many of the concepts applied to *Jason* have been adopted by MBARI in the development of a new ROV dedicated to scientific missions–the *Tiburon*–described later.

The Japan Marine Science and Technology Center (JAMSTEC) is developing a family of *Dolphin* ROVs for scientific missions and for recovery of the *Shinkai* manned submersibles. These vehicles are hydraulically powered and are similar to oil field ROVs, except in their depth capabilities and their use of fiber optics for data transmission. The *Dolphin* 3K, a 9,843 ft (3,000-m) ROV, has been used for geological and biological research operations. More recently, they have completed the development of the *Kaiko*, which has reached the deepest part of the ocean–37,000 plus feet (11,278 m) in the Mariana Trench.

The Institut Francais de Recherche pour l'Exploitation de la Mer (IFREMER), long a developer and user of systems for deep exploration, is now developing a 19,685-ft (6,000-m) ROV for scientific missions. This system will be operational in 1998.

Advantages and Limitations of Manned Submersibles

Manned submersibles have significant advantages over existing ROVs. The deep submersible *Alvin* has been operating for more than 25 years and has an impressive record of accomplishments to it credit. The US Navy's *Sea Cliff* and *Turtle*, the Russian *Mir* 1 and *Mir* 2, the *Deep Rover*, the *Johnson-Sea-Link* vehicles, the 6,562-ft (2,000-m) *Pisces* vehicles and the JAMSTEC and IFREMER manned submersibles have all created an expectation that deep-sea scientists will physically travel to the sites being studied.

By putting “man in the sea,” these systems provide several advantages. Visual observations are intuitive, because naturally occurring spatial relationships are preserved and binocular vision is largely unaffected. Inertial cues to the observer are consistent with vehicle motion. Manned vehicles are usually relatively quiet, they avoid the constraints of tethers, and they can carry larger payloads and exert greater manipulator forces than most ROVs. Visually cued manipulation tasks may be carried out more easily from manned submersibles, utilizing direct binocular vision. Scientists using these systems are provided with stimuli that can be achieved only via human presence at the research site.

So why use ROVs for scientific investigations? The most serious limitation of manned submersibles, which ROVs directly address, is limited bottom time. Supporting human passengers imposes the need for life support systems, large pressure hull volumes, and the potential for exposure of personnel to hazards. These systems often require large support vessels. The absence of high-speed data links limits the opportunity for involvement of shipboard personnel in the scientific work as it is being performed. This means that whatever data collection is attempted, it must be self-contained on the submersible. The computerized control and navigation systems that are an integral part of advanced ROV systems offer the potential to dramatically improve positioning, manipulation, and survey accuracy. Manned submersibles are generally not computer controlled and lack the precise thrust control, positioning, and maneuvering capabilities of advanced ROVs. MBARI’s new ROV will attempt to provide many of the advantages of manned submersibles while capitalizing on the long duration dives, reduced size and weight, and improved data gathering capabilities that a tethered ROV can offer.

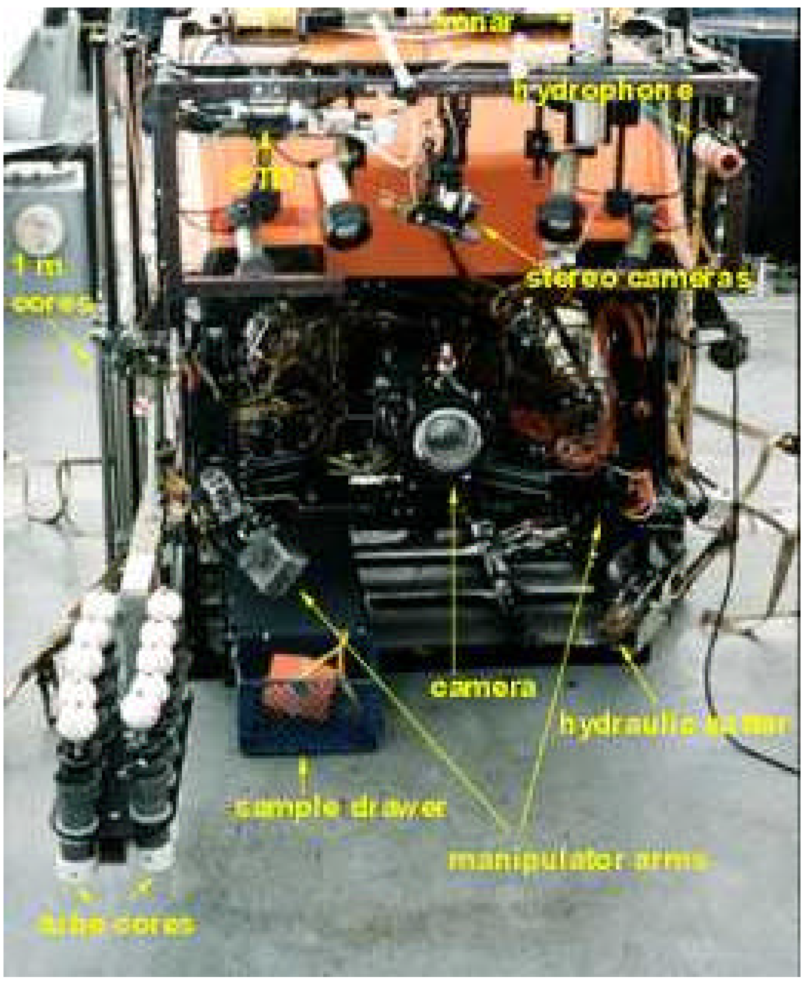
The Ventana

MBARI’s modified *HYSUB* ATP 40-1850, the *Ventana*, provides one of the best examples of midwater and benthic research using an ROV. Changes made to the vehicle include improved cameras, lights, sensors, samplers, navigation, telemetry, and control systems. The use of ROVs for underwater research is a relatively recent innovation, replacing the more traditional methods of using nets or acoustics–and manned submersibles.

***Ventana* with a benthic toolsled**
(T. Craig Dawe for MBARI © 1997)

Manned submersibles, such as the *Johnson-Sea-Link* vehicles and the *Deep Rover*, provide superior high resolution, three-dimensional observational capabilities with full depth of field. However, ROVs provide the greater endurance, greater depth (vs. cost), the ability to operate in adverse weather or hazardous environments, and the ability to provide real time observation from the work site to multiple observers in a much more warm and comfortable environment.

The *Ventana* is depth-rated to 6,070 ft (1,850 m), powered by a 40-hp electro-hydraulic power pack, and uses a 10 optical fiber, Kevlar reinforced tether. In addition to the two seven function ISE-built manipulators, the vehicle has “swing arms” that can be pivoted out from the sides of the vehicle after launch. The swing arms provide additional mounts for samplers, instruments and lights. There is also a “toolsled” that is mounted below the main frame of the ROV that can also carry sampling systems, instruments and electronics packages that do not conveniently fit within the already crowded main frame of the vehicle.



MBARI’s *Ventana* scientific ROV

The observation suite is extensive, with near broadcast-quality color video cameras, SIT cameras, low-light level cameras for bioluminescence investigations, 35 mm still cameras, wide-angle photographic cameras, and a macro/stereo camera with a video viewfinder mounted on the manipulator. Additional locations are available for more cameras if required. The lighting is provided through an array of three 500 W incandescent lights and four 400 W metal halide units from Deep Sea Power and Light, which provide better illumination with lower power requirements.

Instrumentation on the vehicle includes conductivity, temperature and depth (CTD) systems, oxygen sensors, transmissometers, suction samplers, "detritus sampler," flowmeters, tube cores, 3.3-ft (1-m) cores, sampling drawer, lasers for measurements, and a variety of other sampling techniques and devices. Some of the many devices are shown in the following photos. A detailed listing of the many attributes of the *Ventana* is also provided.

MBARI's Scientific ROV *Ventana*

MBARI ROV *Ventana* Specifications

Structure and ballast

- Vehicle dry weight: 2,338 kg. (5,150 lbs.)
- Benthic toolsled, dry: 157 kg (346 lbs.)
- Benthic toolsled, full of water: 236 kg (520 lbs.)
- Coring sled: 318 kg (700 lbs.)
- Midwater sled, dry: 190 kg (420 lbs.)
- Midwater sled, full of water: 318 kg (700 lbs.)
- Configurable ballast c/w benthic sled: 170 kg (375 lbs.)

Power (hotel): 8 kW

- Lighting: 3.4 kW
- System: 1.1 kW
- Science: 3.5 kW

Hydraulic power: 3000 psi

- 40 hp Franklin electric motor (2300 VAC)
- Rexroth A10-25 hydraulic pump

Thrusters (six):

- Two Rexroth A2F with ISE nozzles
- Four Volvo F11-10 with ISE nozzles

Servo manifolds (three 5-valve):

- One Atchley 240 (thrusters and auxiliary)
- Two Atchley 139 (manipulators)

Hydraulic valves (three 8-station, 4-way):

- Manipulators
- Sampler
- Power, thrusters, and auxiliary

Umbilical cable: 1,800 m

- Five #12 power conductors
- Eight multimode fibers
- Two single mode fibers

Navigation Instrumentation

- Altimeter: Mesotech Echo Sounder 807
- Depth Sensor: Paroscientific 8B2000
- Gyro: Humphrey Directional Gyro DG04-0138 (North Seeker)
- Pitch & Roll: Sperry Accustar

Lights

- 4x DSPL Daylight Lamps 400 watts
- 3x DSPL incandescent Lamps 500 watts
- 2x Aux Lights to 500 watts

Sonar

- UDI Sonarvision 4000 500 kHz/200 kHz
- USBL (Ship to ROV): Ferranti ORE Trackpoint II Responder to 3000 m
- USBL (ROV to Beacon): Sonardyne Homer Pro 4000 m capable, 400 m range(LOS)

Speedometer

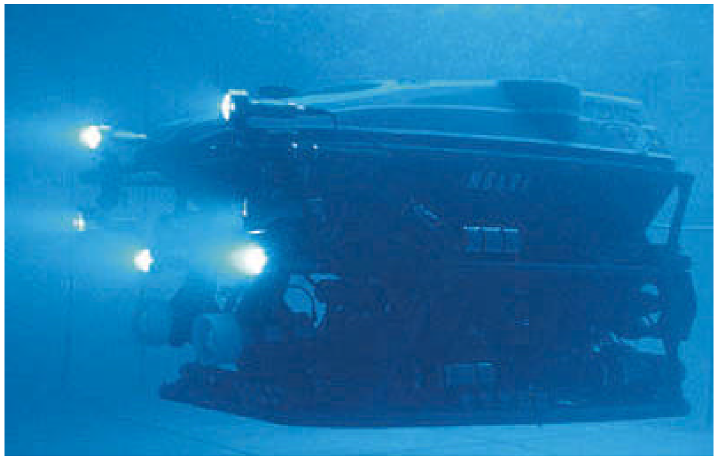
- Savonious Rotor/MBARI Electronics

Camera Systems

- Sony DXC3000 3 chip Camera c/w Fujinon Zoom Lens f1.7 5.5 - 47mm
- 4 x Deep Sea Power & Light MSC2000 Pencil Cameras Lens f4 3,5mm
- Insight Orion Color Zoom Camera
- SGI Video Capture System (direct from RGB Sony Feed)
- Sony digital and Betacam BVM30 Video Recording
- Dynair 30 X 30 Video Switch (ROV control room)
- MBARI/Maxim 8 X 4 Programmable Video Switch (subsea)
- 2 X 4 STC Analog Video to Laser Multiplexers

Mission Requirements Drive the Tiburon

The mission requirements for the MBARI's new ROV–*Tiburon*–have driven most of the design decisions and the overall configuration of the system, although it would be impossible to anticipate all tasks to eventually be performed by the system. MBARI's deep ROV research will focus on geochemical processes, physics, geology and biology. Missions for which the ROV is designed include:



MBARI's ROV *Tiburon*
(David French for MBARI © 1997)

- Instrument placement, retrieval and support.
- *In situ* experimentation.
- Ecological studies and observations (midwater and benthic).
- Sampling and light coring.
- Surveys of environmental parameters.

These missions will require the vehicle to conduct the following functions:

- Transect - for quantification of animals or other target types, substrates, or zonal patterns.
- Hover - to observe features, with minimum thruster disturbance.
- Follow - to follow moving targets along specific environmental features or along a pre-set grid.
- Return - repeatedly to designated sites.
- Collection - object retrieval and transport to the surface.
- Manipulation - a broad range of interactive tasks.

On all of its missions, the *Tiburon* performs as the front end of a data management system that supports general scientific use. Data from the core sensors on the ROV are made available to all of MBARI's scientific researchers.

A detachable toolsled module provides the user-defined package that is configured for specific missions. The toolsled module is designed to be quickly detachable, minimizing the time required for reconfiguration between dives and allowing considerable latitude to the scientific users. Sufficient power must is available for equipment in the various toolsled configurations.

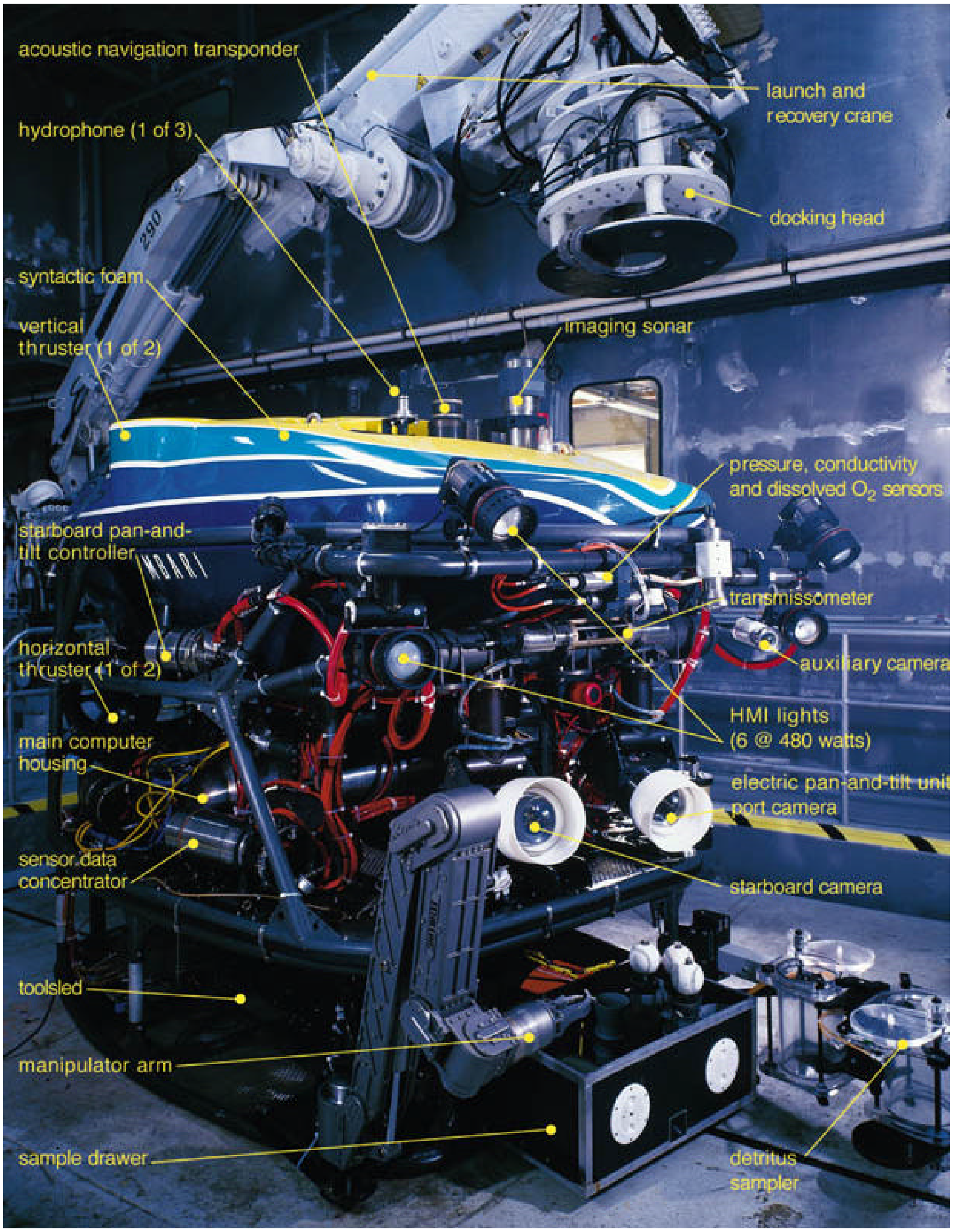
The need to make observations of marine organisms imposed the requirements that acoustic noise and water disturbances be minimized and that a zero light emission capability be provided. MBARI's emphasis on video as a primary source of both qualitative and quantitative information led to an emphasis on high-quality video, excellent general-purpose lighting, and high accuracy pan and tilt mechanisms to aim the cameras. Pan and tilts for the lights provide adequate lighting over the full range of camera motion and imaging requirements.

Precision surveys using video, sonar, and other sensors support studies in ecology, geology, and physical oceanography. *Tiburon* also supports deployed instrumentation and experimental equipment. Sampling gear and manipulators are used for much of the interactive work that is conducted.

The design of the *Tiburon* took several issues into consideration beyond the usual requirements of reliability, maintainability, safety and user friendliness. The vehicle had to minimize acoustic emissions and disturbance of the water around the vehicle to minimize impact on the environment and avoid interference with acoustic devices. Fish are believed to be insensitive to acoustic noise above approximately 7,500 Hz, and to have peak sensitivity at approximately 1,500 Hz. The system was designed specifically to minimize acoustic emissions near this frequency.

The system offers a high degree of controllability for precision measurements and operator friendliness. Precision survey and manipulation demand high accuracy in navigation and positioning. Computer systems not only control the vehicle precisely but also provide the flexibility and expandability to support vehicle control architectures that will be developed in the future. Providing high digital data rates and high fidelity in that data was another primary requirement. The quality of the video signals must be preserved as they are transmitted to the surface and recorded. Instrumentation provided on the vehicle includes:

- High resolution color video with zoom, high accuracy pan/tilts.
- HMI lighting
- Acoustic doppler speed log
- Conductivity
- Temperature
- Pressure
- Dissolved oxygen
- Transmissometer
- Imaging sonar
- Altimeter (echo sounder)
- Hydrophones
- Manipulator arm



MBARI's ROV *Tiburon*
(Greg Pio for MBARI © 1997

The primary location for MBARI's research is in the Monterey Canyon, thus the ROV *Tiburon* is designed with a 13,123-ft (4,000-m) capability. Overall vehicle specifications are shown in the following table.

MBARI ROV *Tiburon* Specifications

Depth Capability

- Maximum depth: 4000 meters (13,123 feet)
- Minimum operating depth: 100 meters (656 feet)

Forward speed

- 1.5 knots (maximum with no tether drag)
- 0.25 knot (at 4000 meters)

Vertical speed

- Descent: 50 meters/minute
- Ascent: 25 meters/minute

Vehicle weight

- Tiburon + toolsled maximum: 3356.6 kg (7400 lbs.)

Payload

- Maximum toolsled weight: 499 kg (1100 lbs.)
- Maximum toolsled weight in salt water: 204 kg (450 lbs.)
- Variable buoyancy capability: 68 kg (150 lbs.)
- Adjustable at 2.27 kg/minute (5 lbs/minute)

Power

- Total power available 15 kW
- Thruster motors: 6 @ 3.7 KW (5 HP)
- Thrust: 978.56 N (220 lbs.) each motor
- High voltage: 240 VDC (±15%)
- Low voltage: 48 VDC (±15%)

Toolsled Interfaces

- Electrical Power: 20 Amps @ 250 volts (5 kW)
- Communications: RS485 serial bus, RS232C, Ethernet (802.3)
- Hydraulic Power: 13.25 L/min (3.5 gal/min) @ 17,237 kPa (2500 psi)

Hardware and software features summary

- Mission-specific toolsled packages—benthic and midwater
- Precision manipulator arm
- Integrated scientific sensors and data logging
- Internet compatible data transmission and user displays
- Control room displays
- Adjustable high resolution video cameras with coordinated lighting
- Stationary video cameras and lights
- Video recorder (Digital Betacam)
- Fiber optic telemetry
- Electric thrusters for precise control, high thrust levels, and quiet operation
- Variable buoyancy system for low-disturbance operation at all depths and during sampling operations
- Equipped to deploy tools and collect samples
- Provision for placement, servicing, and retrieval of instrument packages
- Electric and hydraulic power available for equipment not normally part of the ROV

Harbor Branch Oceanographic Institution

Harbor Branch Oceanographic Institution (HBOI)–HBOI is an internationally recognized non-profit marine research institution dedicated to using and protecting the ocean for the benefit of mankind. One of their many divisions, which address everything from aquaculture to biomedical research, is the Marine Operations Division that operates three surface vessels, two manned submersibles and several ROVs. HBOI has been designing, building and operating underwater vehicles since its founding. In addition to their manned systems, HBOI has developed purpose-built ROV for tasks ranging from submarine rescue to underwater inspection and work, along with many successful vehicle handling systems. Today, their experience and capability is being applied to AUVs to be utilized by scientists and the military alike in solving many difficult and dangerous tasks being performed by man-in-the-loop systems.

HBOI also is one of the world leaders in underwater instrumentation and imaging systems, including such advanced devices as the application of lasers for focus and range finding, 3-D scanning laser imaging and special TV systems for scientific investigations. Also, HBOI has been a leader in designing and manufacturing underwater tools and work packages for applications from archeology to subsea salvage. Their ROV developments follow.

Rescue ROV.

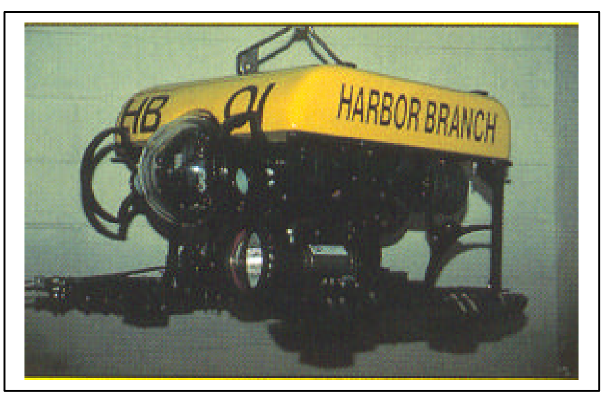
Harbor Branch Oceanographic Institution operates three manned submersibles that throughout the year routinely dive to depths of 3,000 ft (914 m) in support of worldwide scientific research and technology development. The safety of the crew and equipment is paramount in all of HBOI's operations. Areas of operation are often remote and in an emergency the availability of compatible local rescue systems or locating devices cannot be relied upon to ensure a successful rescue. Therefore, HBOI has now built the first of three second-generation rescue ROVs. The first, called *CORD* (Cabled Observation and Rescue Device), built in 1972, served this function for many years, but now has been retired. The three new ROV systems, one for each HBOI research vessel will assume this vital role.

The ROV system (previous page) consists of a vehicle, tether management system (TMS), skid A-frame and winch with 4,000 ft (1,219 m) of armored umbilical cable, control van and consoles, and power distribution system. The system has been designed to occupy the minimum amount possible of the research vessel's precious deck. During its design, an overriding goal was to produce a low maintenance, high reliability system, which could be both easily operated and maintained. Commercial-off-the-shelf (COTS) components and subsystems employed by commercial ROVs were used throughout to ensure worldwide availability of spares and replacement parts.

The vehicle is a 25-hp electro-hydraulic system configured with two longitudinal and four vertran thrusters. At 5.5 ft (1.7 m) long x 3.4 ft (1 m) wide x 3.5 ft (1.1 m) high, the vehicle weighs only 2,000 lb (907 kg) in air. For search and location, the vehicle carries a side looking and forward looking sonar. The side looker covers a swath of 1,312 ft (400 m) for quick location and a forward looker that covers a 492-ft (150-m) swath for navigation to the endangered submersible and provides a general survey of the area around the sub. The sonars, combined with a short baseline acoustic navigation system, ensure a quick transit to the rescue target. A low light level TV camera (SIT) and variable intensity lights on a pan and tilt unit are used to survey a 360-degree area around the submersible before a rescue attempt is made. The vehicle is equipped with a hydraulic cable cutter capable of cutting 1 1/8-in (2.9 cm) wire rope. The cutter is mounted on a specially designed tool that extends and retracts the cutter up to 2 ft (0.6 m) and rotates it 90 degrees. A powerful five-function Schilling Rigmate manipulator with a unique grabber is mounted on the front of the vehicle.

Other Uses

Although the primary mission of these ROVs will be submersible rescue, they may be used for other applications as well, such as scientific research, search and recovery, range support, underwater archeology and others. One deep-water conversion module, including traction winch and storage drum, is planned that will adapt any of the three vehicles to a 10,000-ft (3,048-m) system.

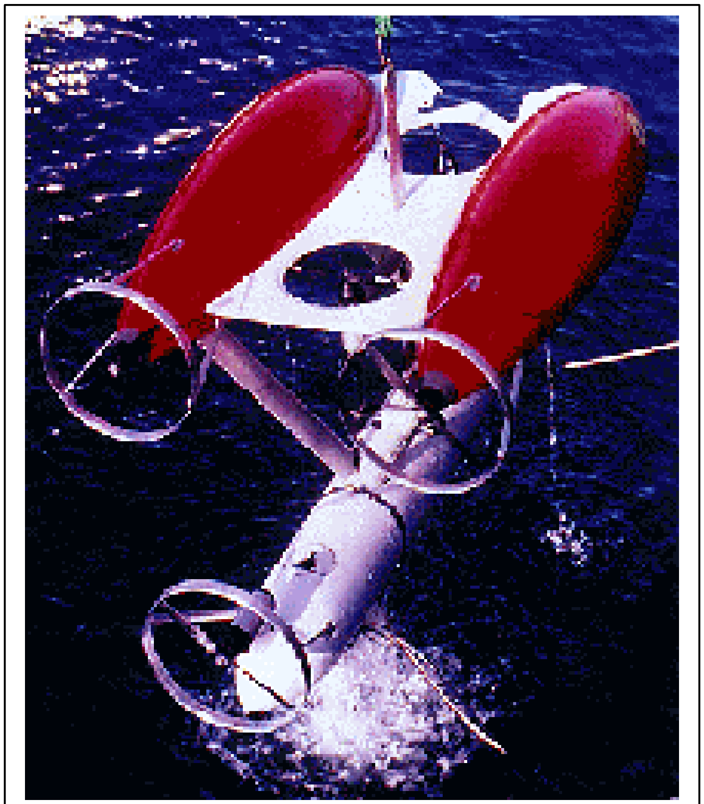


HBOI also operates smaller fly-away ROV systems. *HOMER I*, which was built to explore the *Lusitania* in conjunction with the National Geographic Society, was also used to film the elusive mollusk, chambered nautilus. *HOMER I* was again used in an expedition to Palau, a tiny island nation in the South Pacific, which was sponsored by the BBC and Oxford Science Films. Since the success of *HOMER I*, two more ROVs have been built, a 3,000 ft (914 m) rated *HOMER II*, and a 1,000 ft (305 m) rated *HOMER III*.

Woods Hole Oceanographic Institution

Autonomous Benthic Explorer (ABE)

The Autonomous Benthic Explorer (*ABE*) was designed to address the need for long term monitoring of the seafloor. While manned submersibles and ROVs allow intensive study of an area, they can remain on station for only hours, days or weeks. Consequently, a system that can remain in an area gathering data to fill the time voids between submersible and ROV visits would provide another level of more detailed information on temporal variations. Cameras and other fixed instruments may not always be the best solution to this problem because they have limited spatial coverage and are vulnerable to fouling from bacterial growth or mineral deposits.



After discussions with many scientists studying hydrothermal systems, the concept of a roving robot that could remain working on station for up to a year was developed by WHOI. The robot would spend most of its time "sleeping" in a safe location, then, at pre-programmed intervals, undock, perform a survey with video cameras and other sensors, then redock and go back to "sleep". From these ideas, the Autonomous Benthic Explorer was created and built.

To minimize cost, *ABE* is a three body, open frame vehicle. This allows glass balls to be used for flotation (there are three in each of the two free-flooded, upper pods), and all the batteries and electronics to be placed in a single, lower housing. This separation of buoyancy and payload gives a large righting moment which simplifies control and allows the propellers to be located inside the protected space between the three faired bodies. *ABE* has seven thrusters and can move in any direction. It can travel forward at 3.3 ft/sec (1 m/sec) on about 50 watts to its motors. Navigation and control take only about 12 additional watts.

As presently configured, *ABE*'s principal data is CTD, magnetometer, bathymetry, and monochrome stereo image pairs of the bottom at selected locations. The image recording system has been designed and built in collaboration with Electronic Imaging Systems, Ltd. of Oxford, England. The imaging system is capable of supporting as many CCD cameras as desired with resolutions up to 1,000x1,000. Cameras may be of different types and resolutions. They may be in separate housings and may be aimed in different directions for different missions. The system captures all images simultaneously from a single photoflash. Currently, two downward pointing monochrome cameras are installed for stereo imaging. Each provides an image resolution of 576x768 pixels with a dynamic range of 8 bits. The images are stored digitally on two hard disks. The current disks can store approximately 4,500 image planes (one color image has three planes while each monochrome has only one). They can be upgraded to provide more images than any researcher would want, limited mainly by system power consumption from the vehicle's batteries.

ABE is powered by rechargeable gelled lead-acid batteries to facilitate testing and keep the cost down. Even with these batteries, *ABE* could travel over 31 miles (50 km) in a straight line. In any real mission, however, the energy required to maneuver, operate the sensors and power the flash will limit the range to a fraction of this value. For a long mission, alkaline batteries could be used for an improvement of over four in energy available. Ultimately, lithium batteries will be installed for an improvement of more than twelve in energy, compared to the present lead-acid cells.

In order to accomplish its scientific objectives, and ensure vehicle safety, *ABE* must have reliable and precise navigation and control. Two complementary navigation systems that were proven in previous deep-ocean operations have been selected. Medium frequency range (10-14 kHz) transponders, identical to those used for *ALVIN*, guide *ABE* during descent to its worksite, and are used to navigate for surveys over long distance. With this navigation system, *ABE* has the ability to follow tracklines with a repeatability of several meters.

At the worksite, *ABE* switches to broadband 300 kHz transponders to navigate precisely over a range of about 328 ft (100 m) with a repeatability of several centimeters. This system (EXACT) has been demonstrated on the ROV *Jason* at Endeavour and Guaymas Basin vent sites. With two navigation hosts on the vehicle and two transponders, *ABE* can obtain a range and bearing from either transponder, or it can obtain a long baseline fix when ranges to both transponders are available. In dockside tests, *ABE* demonstrated the ability to hover and follow tracklines within several tens of centimeters, and return to its docking mooring. In addition, *ABE*'s power consumption during closed-loop maneuvers falls well within previous estimates.

Since initial testing in the spring of 1993, WHOI has been steadily building up *ABE*'s capabilities and teaching it to do increasingly involved tasks. In the summer of 1993 it was performing brief autonomous missions using dead reckoning navigation. The video system and the EXACT navigation system were added in the fall of 1993.

The navigation system allows *ABE* to hover (holding x,y,z and heading) in strong tidal currents with only a few centimeters of wander. Forward or sideways movements can be commanded and executed smoothly and *ABE* can find the beacon marking its docking mooring, turn toward it, and dock.

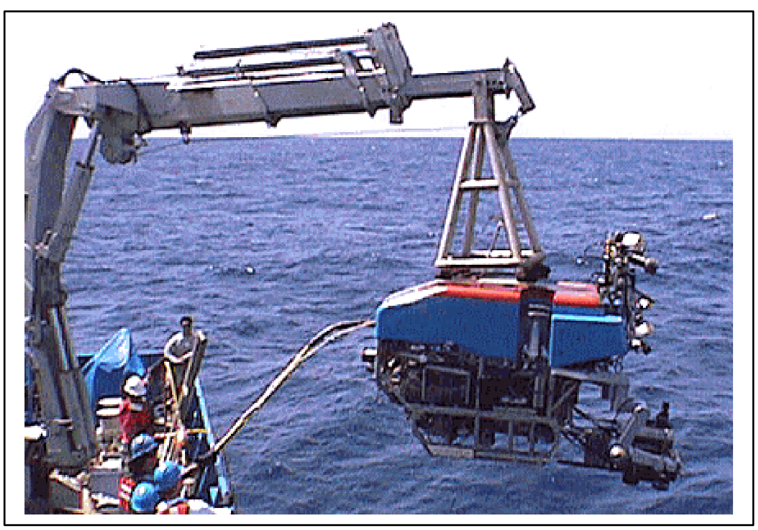
Following initial tests, *ABE* was shipped to join the *ATLANTIS II* in San Diego in conjunction with a series of *ALVIN* engineering dives. *ABE*'s capabilities to conduct repeated dockings, follow tracklines within the *ALVIN* transponder net, and capture images at specified locations were demonstrated.

The first real science mission occurred in mid-1995, when *ABE* was used to conduct a complete magnetometer survey over a lava flow, known to have erupted in July 1993, along the CoAxial Segment of the Juan de Fuca Ridge. A previous survey conducted from the *ALVIN* indicated the presence of a notch-like magnetic low at the center of the new flow, which has been interpreted to be related to the thermal demagnetization of the underlying feeder dike. The survey with *ABE* was designed to investigate how this anomaly changes with time, thereby providing constraints on the cooling and structure of the lava flow. *ABE* flew at an altitude of 66 ft (20 m) above the bottom and covered an area of 0.6 mile by 984 ft (1 km by 300 m) with about 66-ft (20-m) spacing between tracklines,

In 1996 *ABE* was back on the Juan de Fuca Ridge, this time in conjunction with the ROV *Jason*. *ABE* mapped the magnetic field above a feature called New Flow, flew over Cage Seamount and explored the Gorda New Eruption site. Using an improved long-baseline navigation system, *ABE* flew closed-loop tracklines using its in-hull navigation in real time. This made the surveys much more efficient and gave more direct control to the scientific party.

Jason/Medea and ARGO-II

Jason/Medea and *ARGO-II* share essentially the same suite of optical and acoustic sensors and it is envisioned that only one system would be in use at any given time.

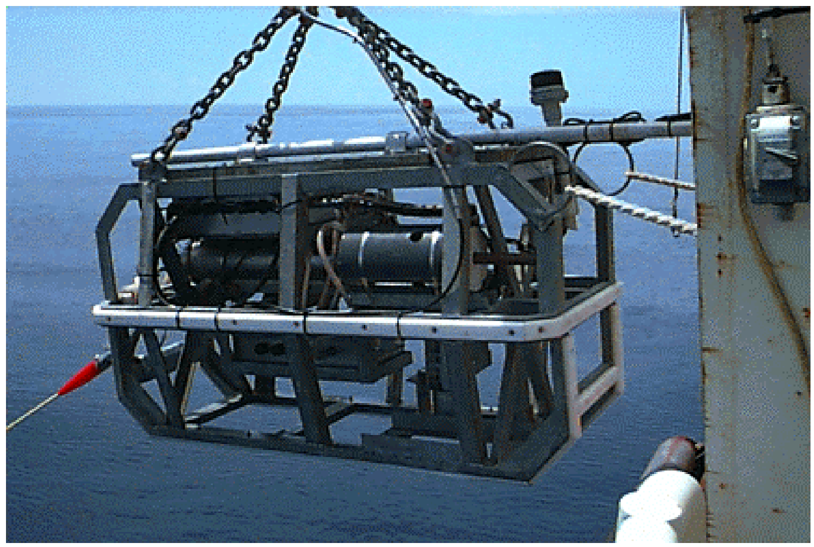


Jason/Medea is a dual vehicle ROV system, with *Medea* serving as a wide area survey vehicle linked to *Jason*, which functions as a precision multi-sensory imaging and sampling platform.

WHOI's *Jason* vehicle during launch

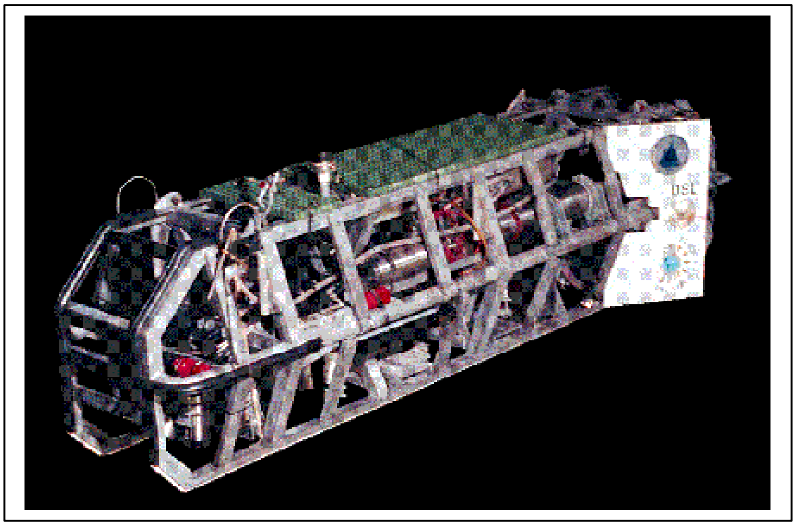
Both *Medea* and *Jason* are designed to operate to a maximum depth of 1,969 ft (6,000 m); they can be operated from a variety of research or commercial vessels. *Jason* is connected to *Medea* by a neutrally buoyant cable 0.60 in (15 mm) in diameter and approximately 328 ft (100 m) long. Like the tow cable, it also uses three copper conductors and three single mode optical fibers, but uses Spectra fibers to provide strength while reducing size and weight. The cable has a working strength that will support a 3,000-lb (1,361-kg) load and the breaking strength corresponds to a 12,000-lb (5,442-kg) load. *Medea* weighs 800 lb (363 kg) in water and is maneuvered by controlling the surface ship's position within a dynamic positioning reference frame.

Medea during launch

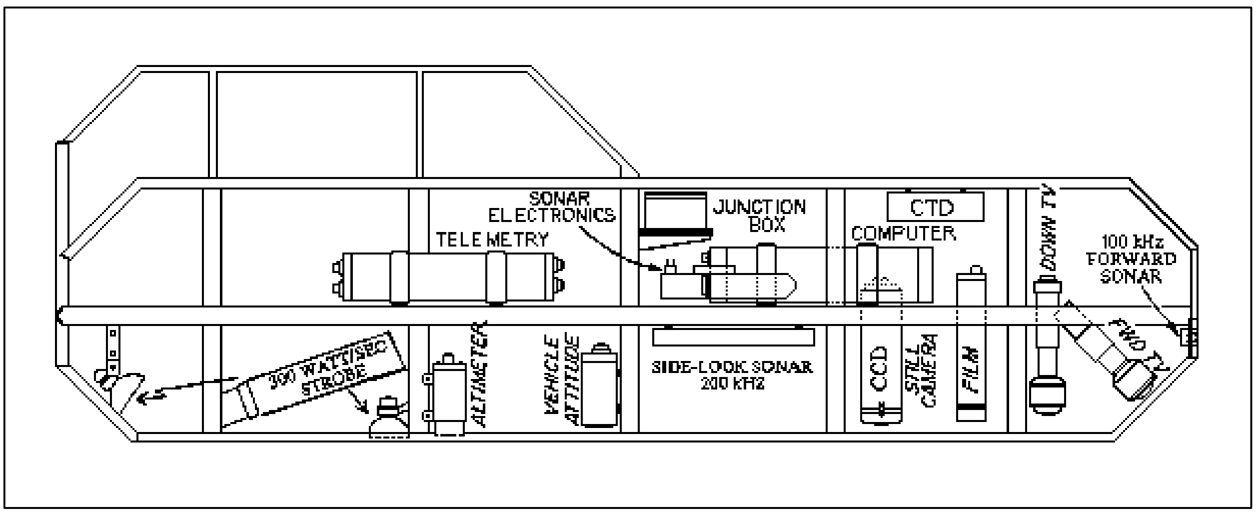


Jason is designed for detailed survey and sampling tasks that require a high degree of maneuverability. It weighs about 2,205 lb (1,000 kg) in air, and is neutrally buoyant at depth. The vehicle is equipped with seven brushless DC thrusters designed to provide a force in any of *Jason*'s axes. Both *Medea* and *Jason* have been designed to be superior, real time, optical imaging platforms with high quality cameras and lighting. The vehicles work together to provide lighting for each other in a fashion not commonly available in other submersible systems. *Medea* is configured with a 1-chip color camera and a silicon intensified target (SIT) black & white camera for terrain identification and visual location of *Jason* when both are operating.

ARGO-II (shown on the following page) equipment and sensors are adjusted depending on cruise-specific requirements and additional equipment (e.g. magnetometer, transmissometer) can be installed. *ARGO-II* is a near-bottom towed vehicle–towed at altitudes of approximately 10 to 50 ft (3 to 15 m) above the seafloor–designed to operate to depths of 19,685 ft (6,000 m). Its powered tethered utilizes fiber optics to downlink controls to various subsystems and data sensors and uplink digital data in both image format and as data-streams.



ARGO II



Schematic of *ARGO II* towed vehicle

Jason/Medea and *ARGO-II* may be configured with the following science data sensors:

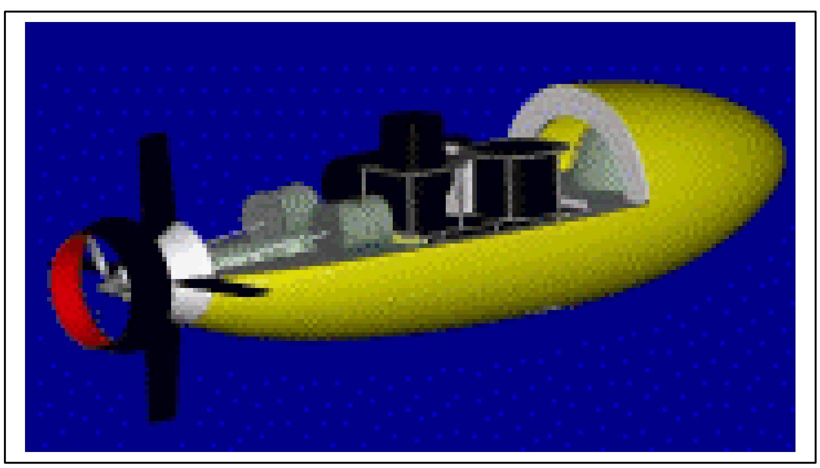
- Attitude: Two-axis inclinometer, 0.1 degree resolution
  Two-axis rate sensor, 0.01 degree/sec resolution
- Heading: Gimbaled flux-gate compass, 0.36 degree resolution
  Gimbaled gyro, 0.1 degree resolution
- Pressure Depth: Bulk semiconductor strain gauge, 3.3-ft (1-m) resolution
- Altitude: 100 kHz updating at 2 Hz, 108-ft (33-m) range, 0.3-ft (0.1-m) resolution
- Acceleration: Tri-axial force-compensated accelerometer
- Navigation: Long base line responder or relay transmitter/receiver
  7-12 kHz vehicle powered or battery operated for emergency location
- Sonar: 100 kHz forward looking for obstacle avoidance
  100 kHz or 200 kHz side-looking sonar
  Mesotech 971 scanning sonar
- Water Properties: SeaBird Seacat CTD

Florida Atlantic University

Florida Atlantic Universities AUV program is resident in their Ocean Engineering Department. FAU is also working on this AUV program with the University of South Florida. The AUV program addresses small, low cost, long range vehicles developed as sensor platforms for educational, scientific and military applications. There are two separate vehicles under development: *Ocean Voyager II* and the *Ocean Explorer* series.

Ocean Voyager II

The Ocean Voyager II began in 1992 as a senior design project to carry a sensor package designed by the University of South Florida (USF). The vehicle has been operational since January 1994 and is continually upgraded and modified by the staff and students.

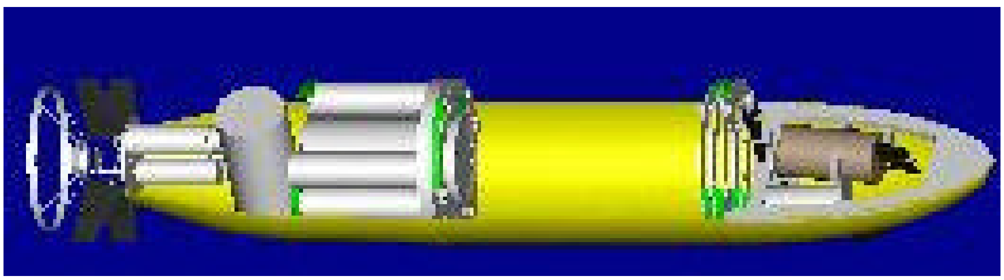


***Ocean Voyager II* (right)**

The *Ocean Voyager II* has been used to test CHIRP sidescan and sub-bottom sonars, long baseline navigation techniques and to obtain coastal environmental data. The artwork on the previous page shows the vehicle with the Bottom Classification Albedance Package, an integrated suite that includes a Xybion multi-spectral downward-looking camera, upwelling and downwelling radiometers, flourometer, transmissometer, and pencil lasers for sizing.

Ocean Explorer

The *Ocean Explorer* is just the beginning of the next generation of several AUVs being developed. This family of modular vehicles will have hulls, sensors and software easily convertible for different payloads. The following configuration is the 3-ft (0.9-m) parallel mid-body version, containing approximately 7.5 cubic feet (0.2 cubic meters) of payload volume. The vehicle is 10.5 ft (3.2 m) long.

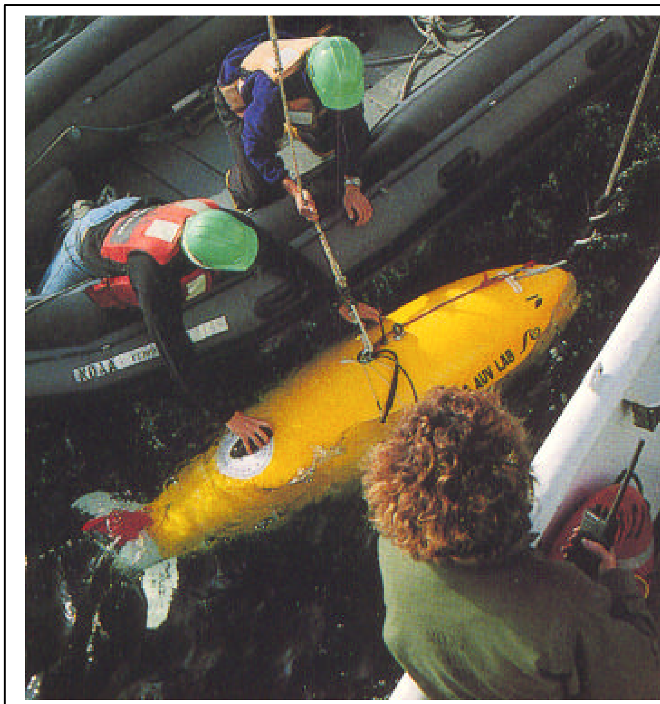


The *Ocean Explorer* of FAU (above)

MIT Sea Grant Laboratory

The *Odyssey* class of AUVs (right) are built by personnel in the Autonomous Underwater Vehicle Laboratory at the Massachusetts Institute of Technology (MIT), through the support of the Office of Naval Research and the Sea Grant College Program. The vehicles are designed for operation to depths of 19,685 ft (6,000 m). At least five vehicles have been built to date.

MIT's *Odyssey* (right)



The design requirements for the vehicle are to use as many commercial-off-the-shelf (COTS) components as possible, and to keep the vehicle small, lightweight, and inexpensive. The hydrodynamic fairings enclose a wet volume and two 17 in (43 cm) diameter glass spheres to house the electronics and batteries. Other fairing designs are available that allow basic components, including control, power, and actuation systems, to be reconfigured for various mission requirements. A two-bladed thruster driven by an oil-compensated DC brushless motor provides propulsion and control. Maneuvering is achieved through two pair of tail-mounted fins in a cruciform orientation. The overall vehicle is less than 6.6 ft (2 m) in length and has a component cost of approximately $75,000. General specifications follow:

- Displacement - 300 to 360 lb (136 to 163 kg) - depending on configuration
- Thrust - 13 lb (5.9 kg) max.
- Depth - 20,000 ft (6,096 m)
- On-board computer - Motorola 68030 processor
- Endurance - 6 - 12 hours typical (40 when in maximized configuration)
- Energy source - 2 kW-hrs of silver-zinc batteries at 0 degrees C.

The MIT program is also investigating technologies that include low power actuators, thrusters with integral motor controllers, acoustic modems, low-power navigation systems, compact side-scan sonars, chemical sensors, homing and docking-coupler nose sections, and imaging systems.

Typical missions that the *Odyssey* vehicles have performed include:

Buzzards Bay - A fleet of four *Odyssey IIB* vehicles conducted missions as part of the Autonomous Ocean Sampling Network (AOSN). Several different organizations used the vehicles to investigate various autonomous docking techniques with a docking station at a remote buoy.

Stellwagen Bank National Marine Sanctuary - Marine habitats were investigated at the Stellwagen Bank in Massachusetts Bay. The *Odyssey IIB* vehicle collected video and acoustic data on the roughness of the ocean bottom, mapping the fisheries habitat on the bank, along with water temperature and salinity data.

Arctic - An *Odyssey II* was operated through a hydrohole in 5 ft (1.5 m) of ice in the Beaufort Sea. A series of out-and-back missions were conducted to investigate Arctic sea-ice mechanics. The vehicle, which demonstrated acoustic communication over ranges of 4.4 miles (7 km), homed into a net for recovery.

Haro Strait - Two vehicles were used together for the first time on a scientific mission in a so-called adaptive sampling mode, which involved reprogramming the vehicles based on the computer analysis of each day’s data. This approach provided new information on how the hot water masses interact in a Haro Strait front.

Recently, Oceaneering has entered a cooperative effort to move the *Odyssey* vehicle, and its low-cost, COTS design approach, into the commercial market.

MIT is also developing a new AUV in cooperation with the Lockheed Martin Corporation for mine countermeasure applications. The flatfish-type AUV, called *CETUS*, is designed to be passively stable, easily controlled and capable of hovering. Based on experience with the *Odyssey*, the developmental goal is to produce a vehicle that's inexpensive to manufacture but durable in service. The *CETUS* vehicle (right) has a single-piece high-density polyethylene hull. The vehicle is depth rated for 656 to 13,123 ft (200 to 4,000 m), based on the type of pressure hull. It uses brushless DC thrusters, lead acid batteries, and is 5.9 ft (1.8 m) long by 2.6 ft (0.8 m) wide. It will have a range of 12.4 to 24.8 miles (20 to 40 km) at a cruising speed of 1.5 to 2.5 knots (2.8 to 4.6 km/hr), with a 5 knot (9.3 km/hr) maximum speed.

***CETUS* AUV (right)**

Naval Postgraduate School

AUV Research at the Naval Postgraduate School (NPS) - As discussed earlier in this chapter, there are many naval missions where AUVs will play a role in the future. With this in mind, the NPS conducts an AUV program under the guidance of the Computer Science, Mechanical Engineering, and Electrical Engineering departments. Their primary testbed is a 6 ft (1.8 m) long, neutrally buoyant, 387-lb (176 kg) vehicle. AUV projects include the study of mission planning, navigation, collision avoidance, real-time mission control and replanning, object recognition, vehicle dynamic response and motion control, and post mission analysis. The AUV has supported well over 50 theses and research papers and will play a key role in educating future Naval personnel on the potential capabilities of AUVs and the technical difficulties yet to be solved.

U.K.'s TUUV Program

The U.K. Marine Technology Directorate Ltd. (MDT) is managing a research program directed toward the solution of UUV operational problems, as identified by industry. This government-industry-academia program is called Technology for Unmanned Underwater Vehicles (TUUV). Since 1986, MTD has supported research programs to improve the capabilities of ROVs. The multi-phase TUUV program's overall goal is to prove that production of advanced UUVs is practical, credible and cost-effective. The initial phases of the program incorporate the individual technologies into a simulation environment where proof of the system concept will be performed prior to transition into an industrial vehicle that will ultimately be constructed and tested.

Underwater Vehicle Research In Australia

The Australian industry and naval defence agencies are active users of underwater vehicle technology. ROVs are employed in offshore oil and gas production facilities, notably in Bass Strait and off the North West coast of Western Australia. A number of specialist and contracting companies support this program. The Royal Australian Navy (RAN) is a user of underwater vehicle technology, and in an international industrial joint venture, a number of *Double Eagle* vehicles are being built by Australian industry for Navy use. The scientific community, notably the Australian Antarctic Division, also uses some smaller vehicles.

Three agencies are primarily responsible for Australian research into underwater vehicle and related technologies. The Centre for Marine Science and Technology (CMST) at Curtin University in Perth, Western Australia, has developed 3D vision systems for ROV applications and has a long-standing involvement in ROV dynamics. The Maritime Operations Division (MOD) within the Defence Science and Technology Organization in Australia is involved in the study of operational performance of Unmanned Undersea Vehicles (UUVs) for the RAN. These two organizations are contributors to the nation-wide Australian Maritime Engineering Cooperative Research Centre (AME CRC). AME has a series of research programs, one of which concentrates on underwater vehicle technology. The present major thrust of the AME program is in vehicle dynamics and position control. A half scale *PAP 104* vehicle has been completed and is being used, with associated inertial and acoustic position fixing systems, to tune numerical models of vehicle performance. In an associated project a one third scale *PAP* model has been deployed using a planar motion mechanism, built by MOD, in a circulating water channel to measure hydrodynamic parameters.

The MOD research program, either carried out within the AME CRC or independently, constitutes Australia's largest underwater vehicle research effort. The work has been performed in three main areas:

- Route Surveillance

- Mine Clearance, involving the use of remotely operated and towed vehicles e.g. *PAP104, Double Eagle MkII* and Type 2093 Variable Depth Sonar

- Rapidly Deployable Systems, involving all types of undersea vehicles including autonomous vehicles.

The MOD activities are currently directed toward the development of both mathematical models of underwater vehicles and the facilities necessary for experimental characterization and validation. MOD are also involved in the development of a six thruster, box shaped remotely operated vehicle. This vehicle will be used as a testbed for navigation, guidance and control technologies. It is anticipated that its utility will be enhanced through other general underwater vehicle research activities. Areas of interest include: navigation, control, hydrodynamic stability, propulsion, umbilical dynamics, guidance, undersea communications and mission management.

Commercial Sector Potential

All too often it is felt that to use an ROV for science, or otherwise, the vehicle must be purchased or developed in house at great expense. However, according to ROV Committee Chairman, Drew Michel, what is being missed is the abundance of ROVs in the commercial sector that are available for hire. More than 1,500 tethered, free swimming ROVs of five different categories were sold worldwide between 1975 and 1992, and the latest estimate of worldwide commercial vehicles now exceeds 3,000. This figure excludes several hundred additional mission specific systems, such as the French *PAP 104* and the US *MNV* mine countermeasure units. Five ROV categories include very low cost, low cost, light work, work and heavy work systems to satisfy requirements.

The 500 plus very low-cost vehicles delivered to date are excellent tools for use in test tanks and tidal pools where excursions are short and currents nearly nonexistent. Their capability is often oversold, but a careful renter of this equipment can make significant use of them for observation of marine life or similar missions in quiet and shallow waters.

Most investigative and small sample gathering work done in open inland and coastal waters can be performed with these low-cost systems. Of the total systems built, approximately 800 fit into this category. The most common of these are the Benthos *MiniRover* and the Deep Ocean Engineering *Phantom* line of vehicles. In the United States alone, more than 50 of these systems are for hire with operators or, less often, available for rent with no operator. The majority is owned by diving and marine engineering firms and is being used to inspect dams, tunnels, piers and other shallow structures. More rarely they are used to observe divers working on offshore oil platforms and in marine salvage ventures.

The light work vehicle category includes systems such as the Perry Tritech *Recon* and smaller International Submarine Engineering *Hysub*. Deep Ocean Engineering and Benthos also have systems available in the upper end of their line that qualify. The most common non-military use for these systems is offshore oil platform and pipeline inspection. The two largest ROV operators in the United States, (Oceaneering International (Morgan City, Louisiana) and Sonsub (Houston, Texas) operate a large number of light-work systems.

Other companies on the Gulf, East and West Coasts operate similar systems in smaller numbers. These are not available without operators but are sometimes deployed with only one person with the intent to use client help in operation and maintenance of the equipment.

Systems described as work-class systems generally have several hundred pounds of thrust and can carry payloads of hundreds of pounds. These ROVs are normally outfitted with high-resolution scanning sonar, multiple TV cameras, dual manipulators, and tracking systems. They can also carry still cameras, special instrumentation packages, and large sample gathering devices.

In September 1992, 194 work-class ROV systems were reported active in the offshore oil industry worldwide. Approximately 120 were based in North Sea ports. Twenty-one systems were reported to be working off the continental United States at the same time. The remainder is based mainly in Brazil and South East Asia. According to Dan White of Technology Systems Corporation, the estimate of work class ROVs working worldwide is presently between 350 to 400. All of these systems are for hire on a day rate basis. To ensure safety and mission success, a minimum crew of three well trained persons, including a hydraulics mechanic, an electronics technician and an experienced marine supervisor, is necessary for the operation of these larger systems. Twenty-four hour operations would require two such crews.

Over 35 additional systems are engaged in non-oilfield activity worldwide. These systems fit the work and heavy work class category. Nearly one-third is owned by the military and is available exclusively for military use. Several others are mission specific (i.e., cable burial). Approximately 10 systems are working on either research or salvage projects and are working now or otherwise could be available for work in science.

The point to be made here is that there are commercial sector ROV systems available for science. The challenge is finding a system that meets the required project schedule and budget. This publication will hopefully point the reader in the direction to find such systems without the need to spend valuable funds to build them in house.

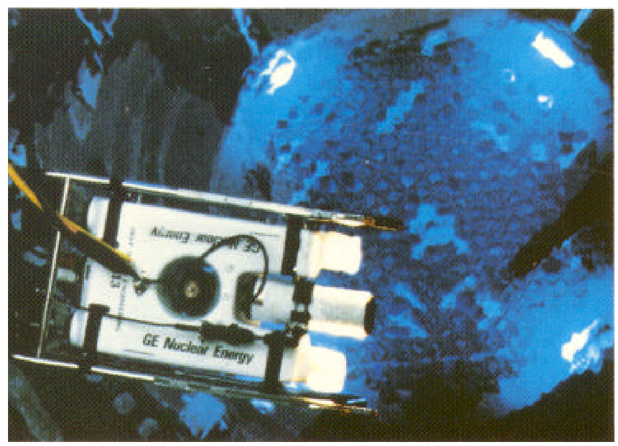
OTHER APPLICATIONS

Inland Operations

When one thinks of conducting inland operations, which are more often than not performed in shallow water, the first approach in the past has been to use human divers. Today, however, a large share of the market is being taken up by ROVs. In most cases, the availability of this technology will not replace divers, but will assist them. Although in extremely hazardous situations, the ROVs will indeed replace divers, albeit for their protection.

For the case of inland operations, just as in offshore operations, every time a diver enters the water, he is indeed entering a hazardous environment. Accordingly, the ROV can play an increasingly important role without ever totally replacing the diver–there are just some things that can not be done with a robot; and, not everyone can afford to use one. Thus, the diver and ROV will have their individual roles in the future, but they will also be required to work together.

The logistics for the inshore use of ROVs is much different than that required for offshore applications. First, you have to get the ROV to the location of the dive–it is a lot easier to pull up in a boat offshore than to carry a vehicle and cable up a mountain to the entry point of a tunnel. Second, the hazards offshore haven't changed much in some time, but the hazards to be encountered inshore can be dramatic: nuclear radiation, zero visibility, severe tunnel and river currents, bodies, lawyers, and the dreaded "zebra mussel."



Nuclear reactor inspection (above)

The initial question one might ask is "How much are ROVs actually being used inshore?" In a recent survey of inshore contractors by *UnderWater* magazine, some interesting statistics were revealed. At the time of the survey, only 25 percent of the respondents had an ROV, but the others showed a high level of interest in them–only 8 percent showed no interest. Of those without an ROV, 80 percent indicated that they planned on getting one within the next two to ten years. Those with ROVs did feel that they had an effect on their ability to compete in the market. The one trend indicated by the survey was that the more the ROVs are used, and accepted, the more work they will probably perform. The biggest complaint was their cost, along with lack of education about the technology in general. In spite of their cost, ROVs have become an integral part of offshore operations.

And, if this analogous trend continues, they will also become an integral part of inshore operations. Prices will come down. "Rent-an-ROV" firms have appeared. The strong will survive–but, the few that refuse to embrace the technology may be the first to go. The statistics indicate that inshore ROVs are here to stay.

The following sections discuss the role of the ROV in the inshore marketplace, areas where the diver and ROV will work together and those where these new systems will provide support to the "non-diver."

A Case Study

Prior to delving into the more specific tasks being performed, let's perform a case study using one of the lead companies that provides ROVs for inland, and many other applications–Deep Ocean Engineering Inc. (DOE). A quick look at their record should clarify the significant role that small ROVs are playing and the diverse array of users that are applying this technology.

DOE designs and manufactures underwater equipment including remotely operated vehicles, manned submersibles, manipulators, and a wide variety of instruments, tools and accessories. However, the point of interest here is that DOE has sold more ROVs than any other company–over 360 vehicles. Most of these sales are in their low cost *PHANTOM* line of ROVs, which are currently being used in more than 30 countries, and 11 different navies. Applications include security, customs and police applications, nuclear and hydroelectric plant and tunnel inspections, offshore oil and gas support, ship hull inspection, treasure hunting, scientific research, environmental monitoring, and broadcast quality filming. They have also been working with NASA to refine a "telepresent" interface for the *PHANTOM* control system; are the world's leading supplier of ROVs for nuclear applications with their the *PHANTOM 150, DRAGONFLY* and *FIREFLY* vehicles; and have a special family of vehicles, the *PHOENIX*, designed to meet requirements that go beyond other capabilities in terms of cable length up to 6.2 miles (10 km), speed up to 5 knots (9.3 km/hr), power, data transmission, and depth down to 26,247 ft (8,000 m). Inshore applications of DOE's vehicles have included:

- Bridge footing inspections
- Dam face, grating and pen stock inspections
- Fish, crab and benthic surveys
- Zebra mussel surveys and removal
- Potable water tank and reservoir inspections, sampling and cleaning
- Intake and outfall inspections
- Lost object recoveries
- Boat salvage
- Archeology
- Side scan ground truthing
- Video documentation
- Body and evidence recoveries

In an effort to show the breadth of ROV users, the following shows DOE's client list, an impressive array of users that leaves no doubt as to the applications and future potential of smaller ROVs, whether for inshore or other applications, as discussed in the following sections.

ABB Reakor GmbH
ABB TRC
Academy Studios
Advanced American Divers
Agner Marine Consult.
American Divers
American Pacific Marine
Applied Research Lab
AquaPlus
Aquatic Science
Army Corp of Eng.
Arctic Venture
A/S EM.Z Svitzer
Bert Instruments
Brazilian Navy
BRC Imagination Arts
Bright Spot
Buffalo Ind. Diving
Bureau of Reclamation.
Can Dive
CanPac Divers
Cape Fear College
Central Soil & Mat.
Central Water Comm.
China Adv. Tech.
City of Honolulu
City of Nassau
City of San Diego
Consumers Appl. Tech.
David Taylor R&D
Deep Sea Discovery
Deep Sea International
Deep Water Recovery
Dept of Nat. Defense
Dept. of Interior
Digilog
Divers Inst. of Tech.
Djupmmynd/Sea Vison
Eason Diving
ECSI
Edge Tech
Egyptian Min. of Defense
Entergy Operations
EDRD
Faroe Islands
Fleet Diving
Florida International University
Forsvarets Materielverk
Fox Island Labs.
Framatome
Frederiksborg Amt
GE
Goteberg University
Griffin Fisheries
Hibbard Marine
Hong Kong Government
Inshore Divers
Instituto Hidrografico
I-ROV
JAMSTEC
K Marine
Kadinger Marine
Kalmar Lansmuseum
Lockheed
Los Alamos Lab
Louisiana University
Marac Electronics
Marco Electronica
Marex International
MariPro
Mark Marine
Mark Tupper
Miljokontrollen
Mamoi Company
NASA
Nat. Marine Fisheries
NURC
Naval Eng. Lab.
NFESC
Naval Post Grad. School
Naval Research Lab.
NSWC
Northeast Marine
Northeastern University
Ocean Systems
Oceaneering
Ohio State University
Otronix Asia
Panama Canal Comm.
Parker Diving
Petro-Baltic Oil & Gas
Rikspolissfyrelsen
SAIC
Saipem
Santa Barbara College
Scholz-Ingenieur-Buro
Scripps
Shastsa County Sheriff Dept
Siemens
South African Diving
SRI International
Storstroms Amt
Swedish Navy
Swedish Police
S.A.U.E.
Tele Danmark
Maritime Aquarium
Tjamo Marinbio Lab
Turmoil Holding
Tyco Submarine Sys
UK Customs & Excise
University of Calif. Berkeley
University North Carolina
University of Plymouth
University of Shanghai
University of S.W. Louisiana
University of Washington
U.S. Coast Guard
Vaktar & Bjaergingart
Vestsjaellands Amt
Virginia Power
Vortex Diving
Walt Disney World Co.
Wash. Fish & Wildlife
Westinghouse
Wisconsin Electric
WINCO
WPPSS

Structural Inspection

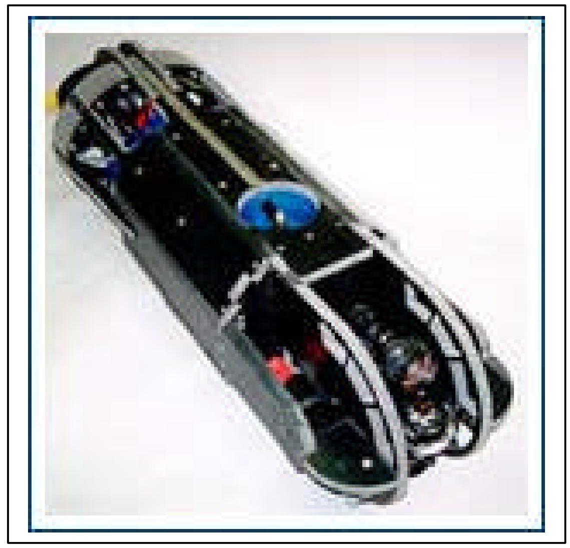
Regardless of the type of structure–bridge, pipeline, dam, etc.–if it is in the water, it is going to deteriorate to some extent, either due to erosion, corrosion, explosion, biologic or geologic activity. Because of this, the world's infrastructure is deteriorating. In the US alone, over 30,000 bridges require inspection. This creates the requirement to determine just how much these structures have deteriorated, and then figure out how to fix the problem, if one exists. Additionally, the inland waters are sometimes the most dangerous to dive in, and that lends itself naturally to ROVs. The sensitive cameras of the ROV can usually see much further than a diver, possibly up to an order of magnitude further, especially in low light conditions. Add to this the ability of sonar imaging systems to see through sediment, algae and other materials that would be opaque to the diver, and the ROV becomes even more versatile.

An interesting use of sonar is performed by the Sonar Scour Vision System (SSVS) developed by American Inland Divers, Inc. Similar to a winged, towed sonar, it is placed in fast moving water from an overhead structure or boat, but in this case, the water is moving and the SSVS remains stationary in the water. The system, which uses a Mesotech 900 sonar, allows inspection for scour–erosion of the material from around a sub-surface structure–in instances where the water current is too fast for divers or standard ROVs. Thus, another good example of the application of technology and unmanned underwater systems to solve an inland problem.

Dams are a major area of consideration, as are the tunnels and pipelines of hydroelectric power plants. Whether an earthen dam that is no more than a reservoir, or the largest power generating station in the world, inspections are necessary. This can become especially important following any severe seismic activity. Dams have failed in the past and will do so in the future, but with an acceptable, cost effective inspection routine, catastrophes can be prevented.

External inspection of sewer outfalls and offshore pipelines is an area where ROVs have been conducting a considerable amount of work, but these tasks are not as hazardous as the internal inspection of tunnels or large (larger than a diver) pipelines. For short distance inspections, with minimal current, divers may be able to do an adequate job safely, but having an ROV along to increase the safety margin, provide documentation and support, and possibly be a “gofer” may be a natural step in the process. However, there are limits to what a diver can accomplish in this category. Many of the areas to be inspected are difficult enough to get into without dragging along an air line from topside and/or a line to provide real time feedback to the topside operators. And, entering such areas on scuba can be asking for real trouble, as noted by the recent deaths of divers performing such inspections. Canada's Ministry of Labor was reported to be considering limitations to such diving, which would include banning scuba inspections in such penetrations, and limiting commercial grade systems to a maximum entry of 300 ft (91 m).

DOE's *Pipeliner* ROV



ROVs can help solve this problem, however, they may need some basic modification to be efficient in such an application. The current in tunnels and pipelines is often high, the visibility can be poor, and the potential for entanglement can be severe, yet it is better to lose a machine than a diver. One company that has approached this area is Deep Ocean Engineering with the development of their "*Phantom Pipeliner*" vehicle (above) for Aquatic Sciences Inc. The goal was to develop a streamlined vehicle that could work within a pipe, 2 ft (0.6 m) in diameter or larger, and travel up to 3,000 ft (914 m) against inflow currents ranging 2 to 3 ft/sec (0.6 to 0.9 m/sec). Unfortunately, the umbilical is still a major problem; it can kick up sediment and cause the turbidity to increase even more in an already limited environment. Therefore, it is better to go upstream if the vehicle has the thrust. And such an approach brings divers and ROVs together again, since the entry to many such tunnels are offshore and may require divers to help the vehicle get through the access door. The future also looks promising, where high-energy batteries, expendable fiber optic micro-cables, and VLCROVs may combine to provide an inspection tool that can be considered expendable.

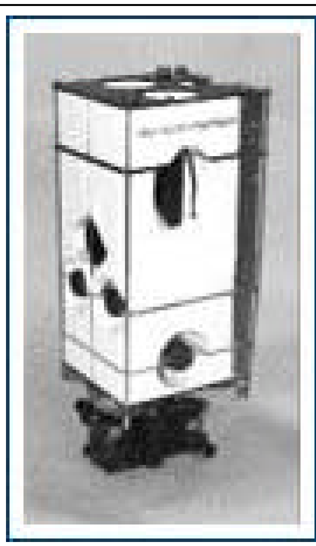
Nuclear Plants

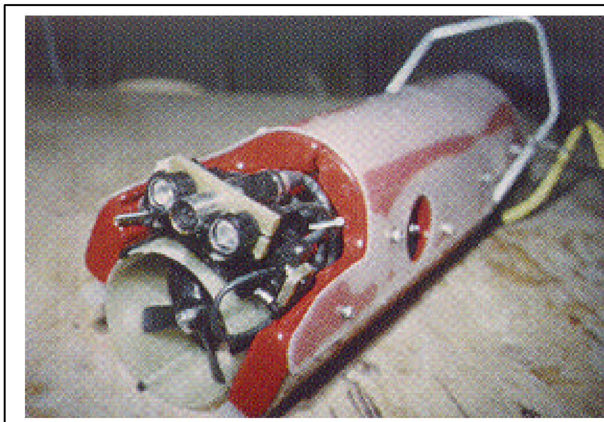
The interesting aspect of the nuclear industry is that it has probably had as much impact on the ROV industry as the ROV industry has had on their inspection techniques. With the downturn of the oil industry in the mid-1980s, many ROV oriented companies turned towards the nuclear industry for additional sales. The result was great strides in the development of television and lighting systems (ROS), manipulators (KRAFT and Schilling), and sensors and small ROVs (Benthos and DOE) that could

meet the operating specifications of the stringent nuclear environment. This caused two key events; several firms stayed in business that may have folded, and their products advanced considerably and were there to take the next step when the offshore business picked up.

There is nothing physically good about working in a nuclear environment. The temperature and radiation effects can play havoc with the inspection system, whether diver or vehicle. The fact that water provides an excellent shield against Alpha, Beta, Gamma and Neutron radiation is the primary reason for committing a diver to the job, as opposed to sending in a technician after the water is removed. And, considering the cost of shutting down a power plant and removing the water, this philosophy is understandable. But, even if the diver is well below the allowed radiation dosage, the potential for an accident is always there. Thus, the nuclear environment is a perfect area to apply a properly designed ROV. Accordingly, this business area was entered by Benthos in designing the *EROV*, and Deep Ocean Engineering with *the FIREFLY, DRAGONFLY, PHANTOM 150* and *the Micro-Pipeliner*; all specifically designed to withstand the nuclear environment.

(Figures - Top to bottom) *EROV, FIREFLY, DRAGONFLY*, and *Micro-Pipeliner*





Civil

The use of ROVs by the police is increasing rapidly as the capabilities of the systems become better understood. What better way to search for a body in a dangerous environment, or take a peek under a ship's hull to see if illegal drugs are attached, than to send in an ROV.

Often, in tasks such as searching underwater for accident victims or for body recovery, much of the job can be done by the ROV prior to a diver entering the water. And, in many cases the task can be completed entirely by remote control. Depending on the depth of the water, the ROV may be able to attach a line, or use its manipulator to bring the item up to shallower water, where divers can complete the recovery. In inland waters, thermoclines in lakes can trap a body, and prevent it from coming to the surface (the cold water prevents gasses from forming due to decay, which makes a body float.) This was the case in a Lake Mead drowning, when the body was found by using an ROV long after the accident. It has been reported that one operating firm has recovered more than 50 bodies.

Whether insurance fraud, murder or just an attempt at hiding evidence, placing it underwater just doesn't work anymore. The ROVs, with their excellent search sensors, can find lost objects much faster than a dive team, and in many cases in situations where the dive team could never be used. The use of advanced sonars, magnetometers, underwater and surface navigation systems, and the documentation of the search by video and photographic cameras make the ROV an efficient weapon in the police departments arsenal.

Environmental

Unfortunately, our planet's lakes, rivers, and oceans have been too often used as a dumping ground for environmental waste; and in many cases it is becoming a hazard as the containers begin to corrode and release deadly toxins or other forms of contaminants. The cost of performing environmental inspections using divers can be time consuming and very costly, not mentioning the potential health hazardous to the diver, who may not know what he is getting into until it is too late. A serious hazard is that the water may appear perfectly clear, or if known to be contaminated, the contamination may be considered to be diluted to a safe level. Both assumptions could be deadly. Unseen contaminants such as bacteria, protozoans, viruses, fecal coliform, cholera, Vibrio vulnificus, Aeromonas hydrophilla, Acanthamoeba, Hepatitis type A, polychlorinated biphenyls (PCBs), and tributylin (TBT) can cause an operating team nightmares. These hazardous items can destroy everything in the body from the liver, kidney, or heart, up to and including the spinal cord. And, many of them really like to live in the water, either floating on the top, pooling on the bottom, or just cruising around waiting for an open seam or faulty piece of diver equipment so that they can enter and destroy the body. Such contaminants have been found following all types of accidents, use of banned (or to be banned substances including ship paints), or just ignorant industrial dumping–and divers have died from them. Following proper procedures will reduce the risk to the diver, but according to Steven Barsky, an expert on diving in high-risk environments, "It's essential to keep in mind that even if you do everything right, accidents are very likely in contaminated water diving. There is no such thing as 100 percent safe contaminated water diving...There is no diving helmet or suit that will make you into a 'superman' capable of diving in any environment." Thus, with the known dangers of working in contaminated waters, what better way to investigate such sites than through the use of an ROV. The vehicle can survey, document and sample the environment possibly to the point that a dive team is not even necessary; or if required, at least they will know what they are getting into. Shown below is Raytheon's new *Tank Ray* robot, designed to inspect the floors of above ground storage tanks without removing the product.

In addition, the general monitoring of the environment will be a growing area: the flora and fauna in the vicinity of offshore oil platforms, the effects of thermal discharge from power plants, nuclear testing and dumping, industrial discharges, underwater dredging and construction, oil spills, sewage out falls, lost ships and cargo. All of these will continue to be areas of concern, and will probably become even more important in the future as the concern for the environment grows.

Raytheon's *Tank Ray* ROV

A good example of underwater assessment of the environment has been the monitoring of the zebra mussel. The mussel was accidentally introduced into the Great Lakes in the US around 1986 and has become a major problem. The small mollusk, about 1 inch (2.54 cm) in diameter, can attach itself to any hard surface, and grow rapidly, adding layer upon layer, and eventually block passages on anything from ships to underwater structures and pipelines. They have favored water intake structures, where a continuous supply of food passes by in the moving water. The invasion has spread to over 18 states in the US and two Canadian provinces and is estimated to become a multi-billion dollar threat in the future.

In a similar fashion, the Arkansas Nuclear One Power Plant was forced to shut down when the Asian Clam clogged its water lines. The Asian Clam's financial impact since its 1980 introduction into the U.S. is also estimated to reach the $1 billion mark. The application of ROVs and/or divers to remove or eradicate the pesky varmints will undoubtedly take a nice share of the available funds.

And, after the pest is eradicated, something has to be done about the damage it caused. This significant aspect of environmental investigations, and/or clean-up, can only get better as a job opportunity. The amount of money being spent on the environmental clean up of land sites is staggering, and compared to underwater sites, those on land are the easy sites to clean up. Once it is determined that the underwater sites, whether inshore or offshore, are to be cleaned up, there is going to be a real opportunity for those in the right place at the right time. The governments, health departments, and environmental regulations will ensure a bright future in this growing area.

Legal

Criminals have used the water to their advantage in countless instances in the past, where the terms "out of sight" solved their immediate problem. The murder weapon would be tossed off a bridge, the ship with its fake cargo sabotaged (such as the 1990 *M/V Lucona* ship inspection by Oceaneering Advanced Technologies), or someone wearing concrete boots was tossed into the water. But, those days are gone. An mentioned above, the ROVs are being used by the police and others to investigate crime scenes, and the evidence being brought back is changing the complexion of the legal system–or at least making criminals think twice about the way they conduct their form of business. Today, through the use of advanced robotic systems, if it is there, it can be found.

Fisheries

The fisheries, and related areas, are prime for the application of ROVs. The ability to assess resources, collect specimens, and provide long term observation remotely will have increasing importance in the future as the once abundant schools of fish continue to diminish due to over-fishing, environmental pollution, or general environmental changes. The ROV, unlike the diver, can provide the operator with the ability to sit at the site for relatively unlimited time, as long as the operating platform can remain in the area. And, with the advances of AUVs, this will change in the future as they can remain even longer, or pass through large areas collecting data. The ROV, with its lights, can attract many species to the area, increasing the potential for *in situ* observation. They can also carry a variety of sensors, providing real time determination of temperature, depth, salinity, etc., while making observations. Such a capability can allow acquisition of data to determine the effect of local temperature gradients, thermoclines, or other factors on the populations, mating habits and predator-prey relationships, to name just a few, regarding the species being investigated.

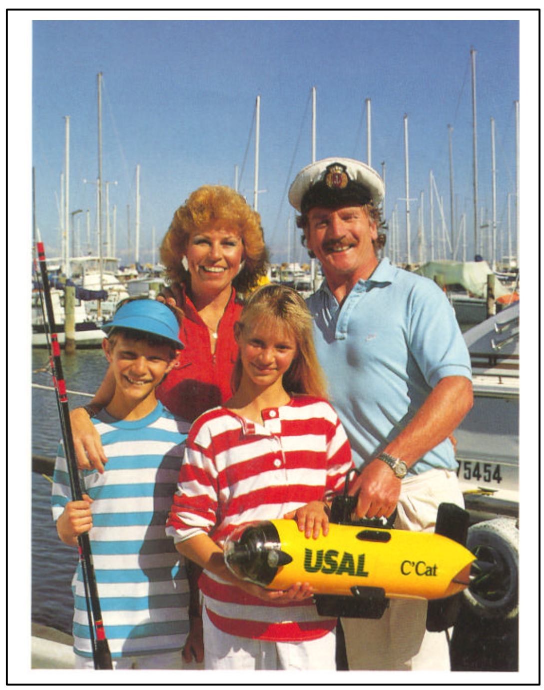
For example, a major area of concern has been dolphin kills in the tuna industry. ROVs have been used to observe the fishing equipment, inside and outside the trawl nets, and the effect of life saving techniques for the innocent bystanders–dolphins.

Treasure Hunting

Treasure hunting has become big business because of ROVs and their advanced technological capabilities. Some have lost money while unsuccessfully looking for lost galleons or sunken ships laden with wealth, however, there are also a lot of new millionaires out there who have fulfilled their wildest dreams, and a lot more who just enjoyed the thrill of the hunt and were satisfied in a job well done.

The most electrifying example of treasure recovery is that performed by the Columbus-America Discovery Group. They located the wreck of the *SS Central America*, and using an advanced ROV designed specifically for treasure recovery, brought back the ship's treasure of gold coins, gold bars, gold nuggets and gold dust, in addition to a wealth of other artifacts. The side-wheel steamer sunk during a hurricane in 1857 in 8,000 ft (2,438 m) of water off the Carolina Coast. A best selling book, *Ship of Gold in the Deep Blue Sea,* was written on the topic.

One fact that cannot be evaded is that today's technology has changed the rules of the game in the search for treasure. It is not necessary to have deep ocean equipment such as that used in the search for the *Titanic* or the *Bismarck*. Many are finding lost wrecks with a combination of a lot of good research, and some cost effective towed side scan sonars. And, depending on the depth, the contents are being brought up using divers and/or ROVs. If you think about it a little, where do you expect to find most of the wrecks–on the rocks–which means they probably went down near shore in relatively shallow water.



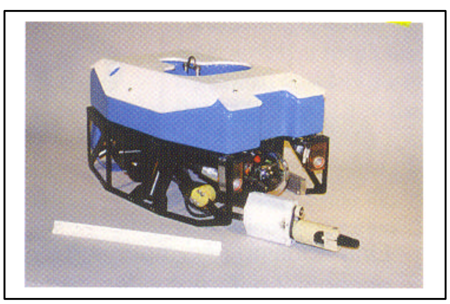
Personal Use

For those who don't dive, and still want to see underwater in real time, ROVs can provide a relatively cost effective answer. With the price of vehicles going below $5,000, and color cameras to display the beauty of the nearby reef, today's ROVs are becoming the gifts for those who have everything–even appearing on the cover of Hammacher Schlemmer (see figure). No longer does the non-diver and his family have to miss the beauty and wonder of the deep–they can stay on deck and have it too. And, there are also the practical aspects of such small vehicles being onboard a boat, such as the ability to check the anchor, inspect the hull, determine why the propeller won't turn, and many other possible scenarios. This applies as much to small weekend pleasure craft as it does to gigantic oil tankers and aircraft carriers. With the threat of limpet mines being placed on a ship's hull during a conflict, such a self-inspection capability can become very important to a man-of-war.

Another situation to consider is the potential for the ex-diver, who can no longer go underwater–whether for pleasure or for work. There can be a lot of satisfaction for the ex-diver who is able to keep his talents honed by turning from diving to operating an ROV, using the vehicle either as a diver's buddy or for one of the many other applications previously discussed.

And for the researcher who never learned to dive, and couldn't afford the expensive vehicles used by others with better-funded programs, the technology has finally arrived at his doorstep. The ability of ROVs to perform investigations, underwater work, or just take samples and gather data is progressing to the point that no one in the future will have to be excluded from the ocean world. The possibilities are limited only by one's imagination.

Education



Another area that should not be ignored is that of education. Deep Ocean Engineering has provided two of their *PHANTOM 150* vehicles (figure to left), to the Tech Museum of Innovation in San Jose, California. Children in the museum will use them. Whether as a toy or an educational tool, the *PHANTOM*'s survivability should get a real test.

ROV/Diver Operations

ROVs will not totally replace divers, regardless of the concept portrayed in the photo to the right, however, they will work continue to work together. Previous sections have addressed the many areas where divers and ROVs may be working together, and the safety they provide each other. However, there is always the problem of the harm one of them can do to the other; this could include the effect of explosives, thrusters, dropped (up and down) tools or equipment, electrical shock, entanglement, etc. Thus, care needs to be taken in the following areas:

- Umbilicals - having two lines or umbilicals in the water at the same time can always lead to problems. This can include lift lines, guy wires, diver umbilicals, the Bell wire or umbilical, anything that is in the vicinity of the ROV. Care must be taken in such situations to ensure that the diver is not placed into a situation that would prevent him from returning safely to his bell or to the surface.

- Thrusters - the fear of being sucked into a thruster is not the problem it once was. Today's modern thrusters are designed with protective covers that block entry of foreign objects, while giving way to allow increased thrust. But care should be taken regardless. The biggest threat to the diver regarding thrusters is that the vehicles are becoming very powerful and can respond quickly. The diver's body will do very little to stop the momentum of a several thousand pound vehicle moving toward an underwater structure–neutral buoyancy doesn't eliminate mass.

- Electrical Shock - this is probably one of the most critical concerns to the diver. Today the problem has been somewhat reduced because of the development of excellent ground fault interrupts (GFI) that shut the electrical system down before the diver can become injured. However, it is a complex and poorly understood area. A reference on this topic is the AODC 035 publication "Code of Practice for the Safe Use of Electricity Under Water" available from IMCA (address at the end of this section).

- Who’s in Charge - the diver supervisor or the ROV supervisor? For safety reasons that are obvious, the diver has priority, and thus the diving supervisor has authority over the ROV supervisor or pilot. In an emergency situation, the safety of the diver is critical and the ROV is expendable. With that in mind, all other aspects of planning, organization and chain of command should follow the same rationale

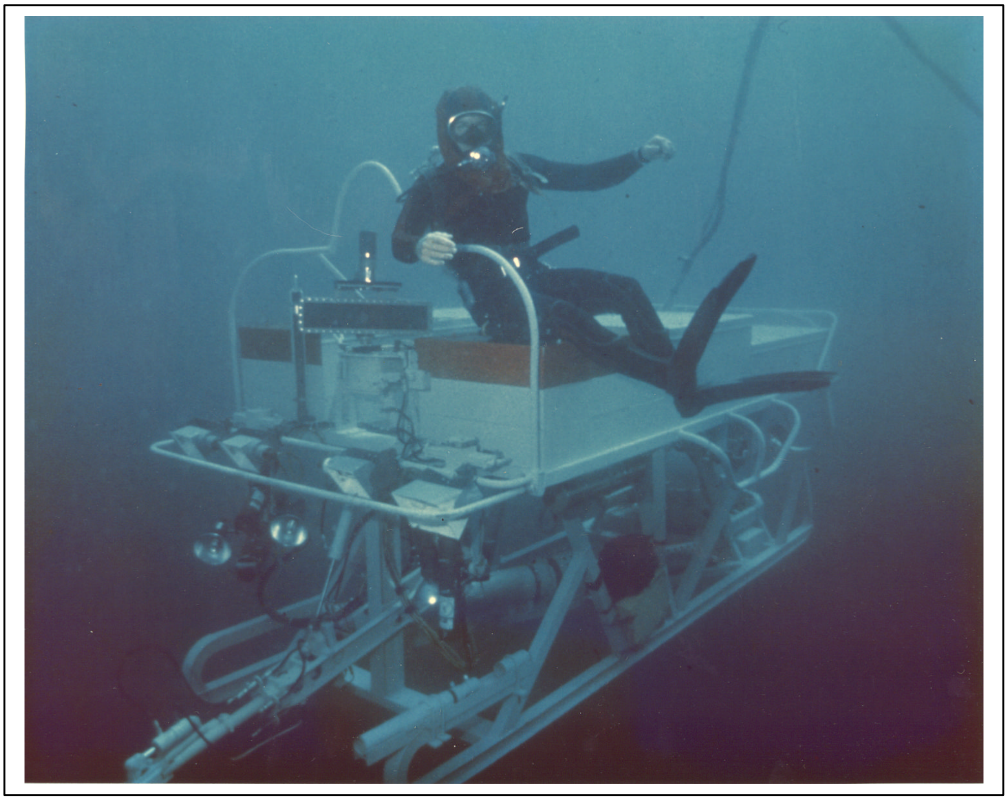
- Contaminated Water Operations - The ROV must undergo decontamination procedures similar to a diver in this situation. This will include the requirement of having the proper decontamination equipment, solutions, etc., on hand and ready to go before the dive, and then using them to conduct the decontamination afterwards. And, don’t forget, in many or most cases, the now contaminated water and solutions used to decontaminate the ROV must be captured and disposed of according to stringent regulations. In addition, the operators who have to clean the equipment will require proper decon gear, just like other hazardous material type equipment used in environmental clean up operations. The operators must be protected also, they can become contaminated as easily as a diver–a virus is a virus–and many of the organisms can quickly enter a wound or other warm opening and cause an infection.

- Training - In this case, training is being discussed with successful business practices in mind. Personnel costs add up, and if the same team that goes to the work site can perform the dive if required, or operate the ROV if necessary, then the team size can be reduced and thus the cost of the operation (see cross-training). Training needs to be addressed in the areas of general setup, operation and maintenance of the equipment. Appearances are what may remain in the mind of the person using your services, whether diver or ROV, thus, it is critical that the personnel conducting the work know their equipment thoroughly, are able to set it up quickly, and repair it without hours of down time. The perception of an unprepared or amateurish crew can result in the loss of a follow-on contract.

- Cross training - If the ROV is to become the diver’s buddy underwater, what should the divers be concerned with? First, as mentioned earlier, most of the ROVs are operated by dive companies, especially offshore. Accordingly, divers are already on the team, and if they are not in the water because the ROV is there doing the job, then the obvious place is for "non-divers" to be topside, telling the ROV what to do. This is where their instincts from many hours (years?) underwater come into play. Divers understand the subtleties of underwater work, the effect of currents, turbidity, and the meaning of many clues that may be missed by those inexperienced in the underwater realm. Cross training is the key to an efficient team. If the divers/operators are also adequately trained on the maintenance and repair of the entire system, so much the better.

- Acoustics - the transmission of underwater acoustic energy can injure the diver. This could also include the use of pingers for underwater location and tracking when the diver is in the water.

Through proper planning, the diver and ROV can work together, increasing task effectiveness and in many cases the safety of both.

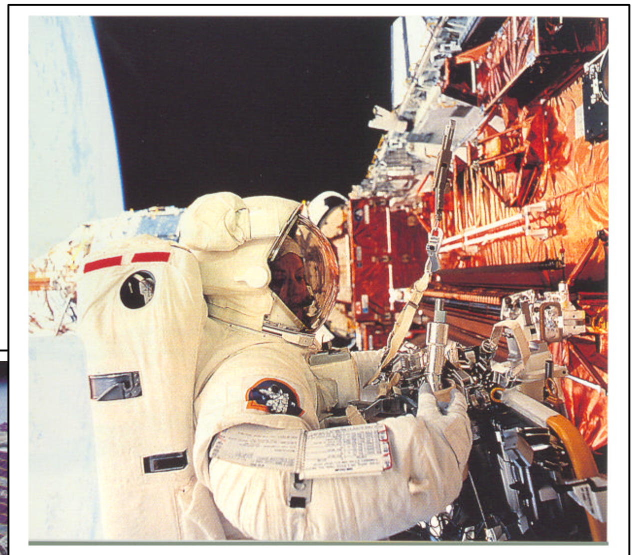


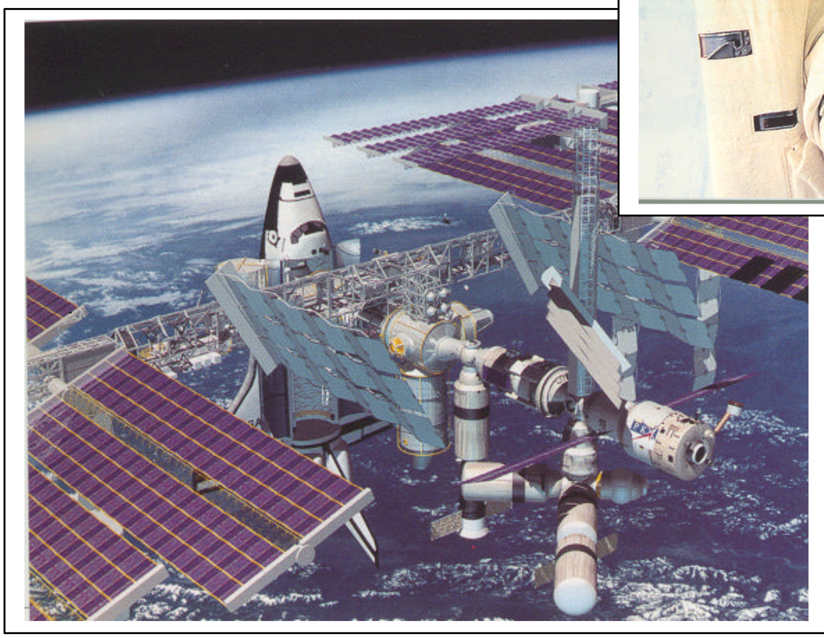
A reference on the topic of divers and ROVs working together underwater is the AODC Guidance Note 032 “ROV Intervention During Diving Operations”. This is available from IMCA, Carlyle House, 235 Vauxhall Bridge Road, London SW1V 1EJ, U.K.

Outer Space

The following section, based on the experience of Oceaneering, addresses the transfer of technology and capabilities between the offshore underwater industry and space based industry.

An interchange of ideas, techniques, procedures, hardware, and personnel between the offshore underwater industry and the space-based industry has taken place over the last 40 years. It is difficult to determine which has benefited most from this exchange. In the end, both benefit and will continue to benefit as we move into the future.





Although there are significant differences between the two industries, there are striking similarities. The similarities are the harsh environments; the dramatic impact of short-comings, deficiencies or failures; and the fact that both industries have a great romantic attraction. Equally profound are the differences, mainly stemming from the environments. Subsea is faced with a dynamic, changing environment: increasing pressures, total absence of light, currents, visual conditions ranging from limited to zero; and the corrosive, invasive aspects of salt water. Space is faced with different, but equally challenging conditions: visibility is generally excellent (half the time you have bright sunlight, often too bright, the rest of the time you have absolute darkness): extreme changes in temperature; ever-present danger of micrometeorite impacts which can be deadly; great distances; and the total absence of a fixed connection between you and your earth-based operational centers.

A History of Cooperation

Going back to the initial successes in subsea, we find many of the players at that time were defense/aerospace contractors such as Lockheed, Hughes Aerospace, General Dynamics, and Westinghouse. These companies used their technological strength in controls, structural design, hydromechanics, and project management to become pioneers in the development of subsea systems, some of which are used in such places as the Santa Barbara Channel, the Gulf of Mexico and Brazil. Hughes Aerospace formed Hughes Offshore and was a subsea hardware manufacturer for an extended period of time. Lockheed Aircraft formed Lockheed Petroleum, which eventually became CanOcean, and developed the subsea one-atmosphere production manifold and wellhead designs and hardware, which were used in the Gulf of Mexico and more broadly in Brazil. This one-atmosphere technology was also being developed by the Seal Group in Europe.

As time went on, the slow growth of the subsea opportunity and the fact that the hardware production would never be great, particularly in the 1970s and 1980s, led these aerospace/defense contractors to pursue other opportunities. This was also a period of tremendous growth in the defense/aerospace business. At that time a number of engineers and managers from these aerospace/defense contractors stayed with the subsea element and many of them became significant contributors in the development of subsea production capabilities.

Development

As the subsea industry evolved, Oceaneering and the subsea industry developed a broad range of engineering, hardware, installation, IMR and intervention techniques evolving from diver-based to one-atmosphere to robotics. In addition, Oceaneering developed a sophisticated analytical capability for defining subsea work, and for developing the most efficient and cost effective methodology of executing this work based on the various types of work systems available. They also developed interface technologies and hardware that allowed a series of remotely operated vehicles and work packages to perform inspections, maintenance, replacement and repair on deepwater subsea satellite facilities. The first integrated example of this was the Placid-Green Canyon 29 template in 1,500 ft (457 m) of water, which had over 400 tasks that were carried out and/or supported by remotely operated vehicles. Using a series of tools and tooling packages, the Green Canyon 29 development was the basis for significant proof of concept, and a confidence builder in the use of ROVs to support deepwater facilities beyond the depth of human intervention. The evolution of this capability has continued into water depths greater than 3,000 ft (914 m). The Norsk Hydro Troll Oseberg Gas Injection (TOGI) project set an industry standard in the North Sea for ROV intervention in deepwater facilities. These projects became the basis for a broad range of subsea facilities which oil companies have installed over the years and are being supported by a series of remotely operated vehicles and a variety of interfaces and tooling packages.

Oceaneering's ROVs now carry out extended work programs in 25,000 ft (7,620 m) of water using a series of five different ROV systems. Essentially the ability to carry out work in the oceans is now independent of depth. What has yet to be implemented is the work task analytics which Oceaneering developed to define work tasks, to quantify difficulty, to establish limiting factors, and to identify which variables can be changed to reduce the difficulty and or cost of any individual subsea task. This analytic methodology has been expanded and is a powerful tool which will find significant use as the costs and difficulties associated with more sophisticated subsea facilities become apparent.

Transfer of Technology

In the mid 1980's, Oceaneering determined that there was an opportunity to take our subsea work expertise and expand it into a space-based business with NASA and major aerospace contractors. The undersea capabilities developed by Oceaneering were viewed to be analogous to those that would be required on satellite repairs, space station maintenance and repair, and other space-based projects. With that in mind, Oceaneering Space Systems was set up with four subsea engineers. The individual selected to run it–Mike Gernhardt, an oilfield diver and development engineer with diving, life support and robotic experiences–is now an astronaut with a first shuttle flight under his belt. Oceaneering used the subsea techniques, technologies, hardware, and capabilities they had developed to show NASA a proven way of executing work similar to what they were just beginning to face as they developed their new space based facilities. Oceaneering’s experience, good and bad, over the years led to safe, reliable, cost-effective work capabilities, starting with diver intervention and moving on to one-atmosphere systems, such as *WASP*, and culmination with remotely operated systems and a series of sophisticated tooling work tasks and interfaces. This experience and expertise was directly applicable to the evolutionary cycle that NASA was beginning to enter.

Work Task Analytics

In conjunction with TRW, Oceaneering used their subsea work task system methodology to develop a sophisticated task complexity algorithm (TCA). The TCA analyzed the task to be performed through a series of methodologies to come up with a way to define a task or difficulty, to define the variables, and to analyze how modifying the variables would reduce the complexity, time or cost of executing any specific task. This task complexity algorithm was then tested using a large number of subsea operators to verify the mathematical model and its ability to evaluate a task and to predict how the changing of any single variable would reduce the task difficulty. This testing showed a high correlation and verified that the TCA accurately reflects the reality of a situation. In addition, an opportunity existed to take the more sophisticated TCA and reapply it to subsea based work tasks, particularly as the complexity of the subsea tasks increases and the need to train operators for more sophisticated work techniques increases. The TCA allows the determination of the baseline requirements and the most efficient work techniques and equipment. This can then be applied to the task-specific training of operators. The result will not only be saving of time and money, but also that operators will be trained on the specific aspects of the work that are in fact critical to success.

Manipulator Systems

Oceaneering developed the Remote Manipulator System (RMS) force reflecting manipulator, in conjunction with General Electric, in the early 1980s for use on their one atmospheric arms bell to carry out drilling support and construction work in deep water. The RMS was first used in Oceaneering's two-man submarines and later transferred to remotely operated vehicle systems to carry out increasingly sophisticated work. This evolution from Manned Systems to Remote Systems allowed the difficult transition to manipulator based work performances to be made by initially having a man in the loop, while they better defined, understood, and sorted out the methodology and tooling required to use manipulator systems to execute work previously carried out by drivers.

Oceaneering subsequently used this technology in the development of *DYNACLANP*, the subsea industry's first robotic system that could clean and inspect platform tubular nodes. NASA has a requirement on Space Station specifically for a sophisticated manipulator system to carry out a range of IMR tasks. It has evolved from the Flight Telerobotic Services (FTS) into the Special Purpose Dexterous Manipulator. SPDM has dual working manipulators with a third manipulator that is used to attach SPDM to the worksite interface. There is a remarkable, almost uncanny, similarity in the geometry and layout of the SPDM when one looks at the *DYNACLAMP* and the dual GE arm work station capability that Oceaneering originally developed for NASA known as the *RTAIL*. The *RTAIL* uses two standard Oceaneering force reflective manipulators with an upgraded control system to incorporate the sophistication required by NASA to carry out some extremely precise and repeatable tasks. The *RTAIL* has been used for a number of years in NASA's test tanks to verify work tasks, verify components, verify interface docking and latching mechanisms and to develop training techniques and procedures intended for use with SPDM when it becomes operational in the late 1990s. In addition, the knowledge of Oceaneering's subsea operators was incorporated into the spectrum of evolving work capability for NASA.

The ability to take subsea manipulators with modifications and incorporate them into the basis of NASA's robotic work capability reinforces the direct analogy and transferability of subsea capabilities to space. In addition, this allowed Oceaneering to incorporate, test and refine the task-complexity algorithm utilizing manipulator configurations very similar to what ultimately will be used on Space Station. They then expect to transfer the control and simulation technologies they are learning back to their subsea business in the near future.

Tooling Transferability

In the area of tooling there has been a similar transferability from subsea to space-based applications. In the mid 1980's on the TOGI project in Norway, Oceaneering developed the All Purpose Intervention Interface (APII) docking system which allowed an ROV with tools to dock to the subsea site in a single operation. Valve actuation, hydraulic connections, electrical signal connections, etc. were all incorporated into this single docking interface. Once docked, the work task could be executed with no further ROV activities required. The APII interface also allows subsea equipment to be designed without constraints on spacing or geometry for ROV docking as the APII (or Oceaneering bucket as it is better known), can be installed at whatever location and in whichever configuration is required to best suit the subsea hardware. This flexibility means that there are no re-engineering and costs associated with converting subsea equipment to a robotic supported capability. The Oceaneering bucket was the basis for what has become NASA's standard docking interface on space system, the Microconical. The Microconical is a miniature version of the Oceaneering bucket with changes in size and configuration associated with the types of hardware and loads involved with space-based operations. Space-based operations, because of the zero gravity and because equipment must be designed to be as lightweight as practical, involve low impact loads and forces at the mating surfaces. The result is that the size and strength of space components can be significantly reduced from that of the subsea where a 4,000 lb (1,814 kg) ROV exerting up to 1,000 lb (454 kg) of load typifies the level of load and force involved. However, the concept and the basic design are all analogous between the Oceaneering bucket and the Oceaneering Miroconical. Oceaneering has supplied over 2,000 Oceaneering buckets to the subsea industry. The use of the Microconical will approach 600; there are even similarities in the extent of application.

Other tooling involves the use of the ACFM inspection techniques. ACFM was developed for the subsea inspection of platforms and pipelines. This technology has been refined and repackaged for use in the inspection of space station structural elements, such as fuel lines.

Life Support

Some of the life support technologies of subsea are beginning to be applied to space-based applications. Over the past 40 years we've seen the evolution from scuba through a series of re-breathers to the present day sophisticated mixed gas saturation diving techniques. Oceaneering has applied their background as an industry leader in the evolution of the capability of life support systems for saturation diving to outer space problems. Subsea engineering involved in the development of subsea life support and decompression technologies have developed a system to be used in NASA's WetF and NBL facilities. This Neutral Buoyancy Portable Life Support System (NBPLSS) uses liquid air for the breathing medium. In addition, and equally as important, it uses the liquid air flowing through a cooling garment to cool the subject. The absorption of the subject's body heat is used in the conversion of the liquid air to gaseous air for breathing. The NBPLSS was developed specifically for use in NASA’s neutral buoyancy facility where astronauts train. Normally they use a life support system with umbilical to provide the cooling medium for an astronaut training in the warm water tank. The use of umbilical is awkward and can provide a false replication of the tasks that will be carried out in space in that the umbilical can act as restraints, sometimes a hindrance, other times beneficial. The NBPLSS is totally self contained and requires no umbilical. It is only the third life support system that NASA has certified as man rated. This NBPLSS life support technology, using liquid air as a cooling and breathing medium, is also being developed for use in the fire fighting industry where heat prostration is one of the limiting factors on the fire fighter, particularly those who have to enter high rise buildings and expend high levels of energy without the presence of cooling.

Inspection, Maintenance and Repair Expertise

The offshore business has for the past 40 years been required to develop sophisticated long-term inspection, maintenance and repair programs for their offshore structures. This led to an extensive analysis of the original design criteria, construction techniques, installation techniques, as well as the long term inspection, maintenance and repair. It also led to evaluating the true life cycle cost associated with long term assets. NASA is looking at this experience and expertise as being applicable to the space station. Up to this time there has been no long duration, large scale, space-based facility that had requirements for inspection, maintenance, and repair over many years. Until recently, hardware launched into space with a long life requirement was self-sustaining with the exceptional high levels of redundancy. There was no inspection, maintenance or repair capability. Reliability had to be obtained through extensive and costly redundancy, testing and sophisticated design and manufacturing techniques, which can also lead to difficulties with reliability. However, with Space Station there will be a need for a 30-year life with continually changing hardware due to life cycle growth. As a result there is now a more fundamental approach to the life cycle cost and the life cycle inspection maintenance, and repair requirements that need to be adapted.

The previous examples provide a sketch of the impact that undersea technology has had, and will have, on outer space exploration. The subsea industry is an excellent analog for such applications and, wisely, it is being used accordingly.

CHAPTER 3. WHAT CAN'T THEY DO?

One of the goals of this publication is to explain what an ROV can and cannot do. The following sections will address some of the limitations of ROVs – hopefully to put the proper spin on the ever-expanding promises of marketing brochures and technical information. First, this section will address one of the driving factors affecting ROVs–the environment. Following that overview, additional comments will be made on specific topics such as Operational Footprint and Speed along with a discussion of Fables and Other Dreams.

ENVIRONMENTAL ASPECTS (NATURAL)

The successful completion of the many tasks discussed in this publication depends upon knowledge of the effects of the environment on the ROV system. Although the ROV system is of primary concern here, its operating platform must also be considered since many of the environmental conditions will have extreme effects on it as well. The following discussion of environmental aspects will highlight those areas that affect the system. References to other sections, where more detail can be obtained, will be made.

Depth

The operating depth of ROV's has increased to the ultimate depth with Japan's *Kaiko* reaching the bottom of the Mariana Trench at 35,791 ft (10,909 m). When the original Operational Guidelines for ROVs was published by MTS in 1984, the depth capability of most existing ROVs was only in the 3,000-ft (914 m) range–shallow compared to today's standards. However, that depth was driven by demand and not necessarily the depth capability of the vehicle. The depth capability of the vehicle is generally a design problem, requiring a redesign or respecification of those components that are sensitive to increasing pressure. This causes an increase in the weight (density) of the buoyancy material; pressure housings will grow in both size and weight and sealing problems may be encountered with dynamic systems such as motor shaft seals. A comment made in the original ROV Guidelines–just because "the present market demand isn't high for deep systems, it doesn't mean that the technology isn't available"–was a wise prophecy that has been proven very correct countless times. Today, as market demand drives system requirements, the depths are increased, after all, it really is only a design problem–assuming the funding is there. In general, the governments and military have been more concerned with the deep oceans and, therefore, have developed the technology that addresses this operating range. Vehicles such as *AUSS*, *ATV*, *CURV III*, *Kaiko* and many others have been developed through government funding. The key point to be made here is that you can not take any "off-the-shelf" vehicle and use it at any depth. Although it is only a design problem, the design must be made for the maximum operating depth if success is the goal.

When considering a vehicle for deeper applications, several things should be kept in mind. First of all, the umbilical cable is obviously going to grow in size (length), which will affect the size and specifications of the topside handling system. This usually begins a vicious cycle because as the depth increases, the drag on the cable increases and either the vehicle's operating footprint must decrease or its power must increase. If the power needs are increased, the cable diameter must increase, which increases drag, which increases power requirements, which…! It is not a simple solution and needs to be looked into in detail, especially when combining depth effects with current profiles (see next section).

As the cable length increases, the number of wraps on the cable reel also increases. Depending upon the amount of power being sent down the cable, the inner wraps on the reel could become overheated if adequate cooling procedures are not considered. One method used in such instances is to spray or run water over the entire cable reel.

Whether there is a vehicle only in the water, or a vehicle and TMS, it is still essentially a spring/mass system. Depending on the overall response characteristics of the system, it is possible to enter a dynamic range where "snap loading" of the cable occurs. It has been shown that most cables will pass through this range when transiting to deep depths if the tension on the cable is not kept high. Essentially, snap loading occurs when the tension on the cable goes from a positive tension to a negative tension or slack cable. Thus, when the tension is taken out, due to the cable dynamics, a snap load occurs, which could overstress the cable. The vehicle cages provide a good method of increasing the tension on the cable; however, they don't move through the water quickly, so depending on the sea state, a problem may still be encountered. Thus, if operating in very high sea states the need for a motion compensation system onboard the ship, which helps decouple the ship's motion from the vehicle, may exist. Once again, the fact arises that the umbilical cable gives the ROV its freedom, however, it also causes the ROV most of its problems. Therefore, the depth of application of the vehicle, its platform, and cable dynamics need to be evaluated more critically as the design depth increases. Additional areas of consideration involve the overall operating time involved with increasing depths. The time for a vehicle to travel to a 20,000-ft (6,096-m) depth and back is not small and affects several members of the crew who must monitor the system during its transit. Depending on the operating platform, weather, length of work operation, etc., it could have a major impact on the successful completion of the task. Increasing depth capability is costly and most components (power system, handling system, umbilical cable, TMS, vehicle) will increase in size, weight and cost. And usually, the sophistication of the system will increase, which will affect the cost. The deeper the operating depth, the more concern there will be about the reliability and safety of the vehicle, and the probability of successfully completing the mission. These factors will also increase system complexity and cost. The only thing that usually decreases with depth is the ocean current; however, that current then acts on an increased length of the cable. And, when working deep, don't forget to keep a wary eye on the weather. It's no fun when a vehicle is working deep and the sea state changes for the worst.

Currents

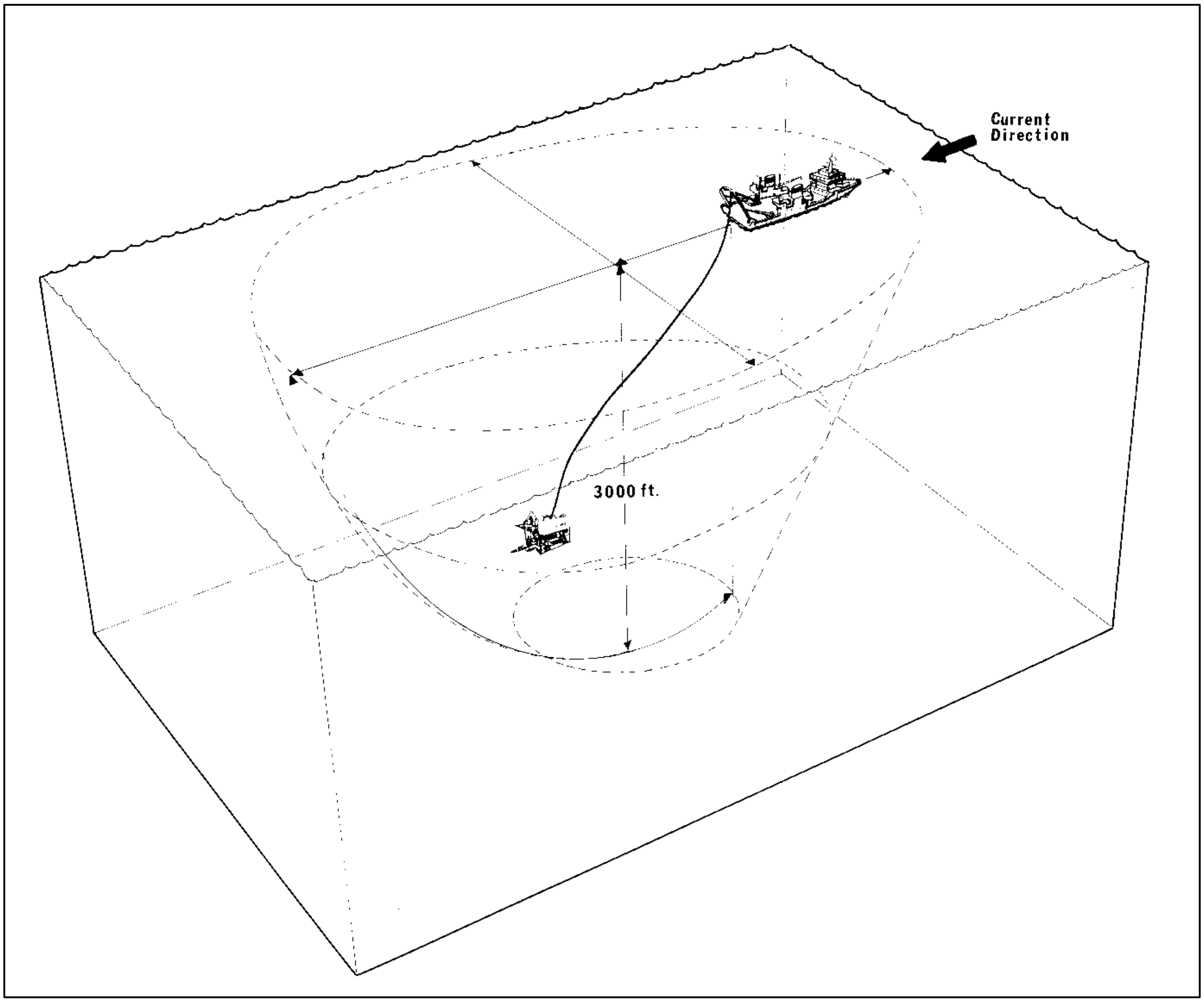
One of the most troublesome of all environmental aspects is the effect of the current on the ROV system and its support platform. And, unfortunately, this is one area where extensive data is not available. Other than near surface currents, and those in harbors and other critical areas, there is very little quantitative data available on current profiles, especially in deep depths. In general, however, the currents in the deeper ocean are less than 0.25 knot (0.46 km/hr). Currents are rarely constant over periods of days or more. Most often there is some average flow plus a variable component usually having a tidal period. This is as true close to the bottom in the deep sea as it is in shallow, near-shore locations. However, the magnitude of both mean and variable components is usually an order of magnitude smaller near the deep sea floor. They are also quite dependent on location with potentially severe local variations. The surface currents, which come into play more severely during station keeping of the vessel and recovery of the vehicle, can be quickly affected by the wind direction.

The effects of currents on the underwater components of the system are dramatic. As explained in the previous section, the relationship between the power transmission of a cable, its diameter and drag is not a simple matter. The effect of current on the cable and the vehicle will drive the system design. Going from 2 to 3 knots (3.7 to 5.6 km/hr) with a vehicle is not merely a power increase of 50 percent, but an increase that must overcome almost twice the drag (proportional to the square of the velocity), requiring nearly 3-1/2 times the power (proportional to the cube of the velocity). Obviously, increasing the speed of a vehicle that already exists isn't a simple matter since the size requirements of the power system quickly grow.

When discussing the current speed capability of an ROV, it is more appropriate to consider the operational footprint of the vehicle/cable system and not just the maximum thrust of the vehicle. The capability of the vehicle to maneuver in the current is dependent upon the amount of cable deployed, the depth, and the vehicle's orientation to the current (see figure next page). Most vehicles will have a better thrust capability in a forward direction than in lateral translation. Thus, a family of footprints can be generated for each system, which can be used to determine the operability of the vehicle in a given current.

The weight of a cable can offer certain benefits in high currents, acting like an anchor for the vehicle; however, this severely limits the vehicle's footprint or excursion area. A TMS also offers this capability, allowing the vehicle to drag its smaller tether horizontally through the current, thus eliminating the cross current drag (assuming you are working into or with the current).

Some vehicle systems use floating (or slightly positive) cables, primarily near the vehicle, to allow the near vehicle portion of the umbilical to float up and away from the vehicle and the object it is working on. The “S” portion of the cable also helps decouple the vehicle from the motion of the vertical portion of the cable. It also keeps it away from the seafloor, preventing it from stirring up bottom silt.



Typical ROV 3-Dimensional Footprint

When launching or recovering such a system, the near-vehicle cable floats on the surface and is susceptible to surface currents. These currents can be severe and quickly get the vehicle into a compromising situation with its support vessel.

Current profiles are not always uniform. Often there is shear, with significant variations in both magnitude and direction as depth increases. This increases the control problems for the operator. On the other hand, even the absence of a current can pose a problem. Currents will carry away the silt and sediment stirred up by a vehicle operating near the bottom. Thus, a slight bottom current is most often beneficial, depending on the type of bottom being worked on.

One of the most important considerations when operating in a high current area is the experience of the vehicle pilot. A poor or inexperienced vehicle pilot can quickly get into trouble in such an environment. Knowledge of the vehicle, its capabilities and limitations is essential.

Only experience will provide an operator with the insight to develop the "operational tactics" to overcome an adverse or unanticipated situation. The proficiency of the operator is a critical aspect of the ROV system and is addressed in more detail in the training section.

ROVs are required to perform many detailed work and inspection tasks around sub sea structures and objects, even in the presence of strong currents. As water flows around the objects, it is accelerated in some areas, decelerated in others and eddies are often formed. As the vehicle approaches the object, it is subjected to the forces created by these variations in water current. These forces can exhibit abrupt changes in direction in all axes (X, Y and Z), as well as in magnitude, when compared to the open water forces on the vehicle. This usually creates difficulty in carrying out the prescribed mission and invariably results in inadvertent impact between the vehicle and object.

One example is the inspection of weld joints on jacket braces, which can range from one foot to several feet in diameter. Since the ROV must work within a one-diameter range of the brace, it will be exposed to local accelerated water velocities as the current flows around the brace. This type of flow sets up vortex shedding (eddies), which break off alternately on either downstream side of the brace in a periodic fashion. The ROV pilot must be able to maneuver the vehicle against these disturbing forces, which can range from 17 to 26 seconds per cycle on a 2 ft (0.6 m) diameter brace in 0.25 knot (0.46 km/hr) water currents; and to 4 to 7 seconds per cycle in 1 knot (1.9 km/hr) water currents. The period varies directly with the water velocity and inversely with the brace diameter. The disturbing force, as above, will vary as the square of the water velocity.

Sea State and Swell

The one thing that is certain in ROV operations is the heave motion of the support ship at the air-sea interface, assuming the operation is not being conducted from a more stationary offshore platform. The motion might be mild to near zero at times, and yet within hours can become violent with the support ship pitching up and down 10 to 20 ft (3 to 6 m) from a neutral base line, and rolling 10-20 degrees. Sea states, which may range from 0 to 6 (Appendix G), are an ever-present consideration for all at-sea ROV operations.

Concerns that must take sea state into account include storage and battening down of the ROV and its components enroute to the station; careful preparations and consideration of safety during prelaunch break-out and launch; realization of the variable dynamic load on the ROV tow or tether cable as the support ship heaves in the surface sea while the ROV, deeper in the quiet sub-surface, remains essentially motionless; the great potential for physical accident and grave material damage during recovery as well as in all other phases of ROV operations. Ever present, an increasing sea state can make the normally difficult task more so by many orders of magnitude.

The cause of sea state is high winds blowing for a long period of time, either a prevailing wind over a long fetch of ocean, or perhaps in a more concentrated area called a storm center. The resulting sea state has a random distribution of amplitudes and wave lengths, and can be characterized as a two-dimensional random process.

At distances far from the storm center, the short waves (sea) diminish and the long waves arrive to create the swells that will gently but firmly cause low frequency heave and pitch motion of the support ship.

Means for minimizing the bad effects of sea state on ROV operations include proper launch/recovery system design, tactical maneuvering of the mother ship prior to launch/recovery, and crew training. Additionally, cages and heavy lift umbilicals (armored cable), which facilitate rapid launch and recovery, are used. Even with these devices, seamanship is most important. In accomplishing launch/recovery, one must take into account sea, swell, currents, wind and maneuvering capabilities of the ship. The basic aim of this exercise is to keep the vehicle away from the ship until the dynamics of the situation is clear, and the crew is confident the vehicle will not come up under the ship and, in fact, can be successfully recovered.

Because of the complex interrelationship between sea, swell and wind, there is no hard and fast rules regarding how to launch and recover at sea. Different size vessels respond differently in a seaway. However, a vehicle should never be launched in such a fashion that the support ship could drift over it. When weather conditions are adverse, launch/recovery operations must be planned in as much detail and with as many options as possible. Execution of the plan must be undertaken rapidly and decisively. The captain of the support vessel must be thoroughly briefed and, therefore, must clearly understand what the vehicle operators wish to do. There must also be good communications among those involved in the operation.

Finally, one must take into account the dynamic motion imparted to the ROV by severe pitching, heaving and rolling of the mother ship. When at short stay, the ROV cable can actually be broken by a sudden motion of the support ship. When at long stay, the catenary of the ROV tether will usually attenuate the ROV’s motion, although precise flying altitude can be hurt by support ship motions. A large ship, which moves less in a sea state, is clearly more advantageous than a small vessel if operations in a heavy sea state are required.

In summary, the cautious advice for ROV handling operations in a heavy sea is: do not do it, at least from a vessel with poor sea state capability. But, this is not always possible in real life. The next rule, therefore, is careful preparation via choice of launch/recovery/stowage system, careful planning, and team training–and remember, the ship Captain is part of the team. A sea state is a two-dimensional random process. There will be a predominant direction, wave length and height. There will also be variations about the mean or predominant values as in any random process. The prudent ROV operator will, therefore, give enormous respect to sea state.

Weather

In a physical sense, any ROV system is relatively insensitive to weather, but, on the other hand, the weather may seriously affect the cost and efficiency of the operation. Variability of the weather introduces an element of uncertainty in operations; for example, fair weather at launch does not categorically lead to fair weather at recovery. Thus, adverse weather contingency must always be a part of effective operational planning, especially for recovery operations.

The various aspects of weather (i.e., wind, fog, precipitation, and temperature) impact the operation in different ways. The primary effect of wind on the ROV system is with respect to the support ship. The level of difficulty in station keeping increases rapidly with wind speed. For this reason, careful design of the propulsor and thruster arrangement on the support vessel is crucial to achieving the maximum weather limit for ROV operations that involve dynamic positioning of the support vessel. Wind and fog are factors that impact transit time to and from the operating site.

Reduced visibility in the presence of fog or precipitation impairs the safety of the launch and retrieval operations. This is particularly the case in emergency recovery caused by the failure of some component of the ROV system. Such events are unplanned and often call for unusual application and stress on ship's gear and ROV handling equipment. Awareness of the increased hazards of unfavorable weather conditions and an evaluation of the probability of a change in the weather must be included in the dynamic decision process that accompanies an emergency recovery.

Fair summer weather environments can impose intolerable temperature extremes on the ROV vehicle during full power deck checkout. It is quite possible for temperatures in the ROV electronics compartment(s) to exceed the design temperature range when it is subjected to irradiation from the sun on a hot deck.

Another component of the ROV system subjected to temperature problems is the umbilical cable stored on the deck-mounted winch. The temperature rise in the umbilical cable on the storage drum is caused by chronic heating of the power conductors trapped by the poor conductivity outward of the multilayer wrap on the drum. This is aggravated by warm air and solar irradiation at the outer layer where the internal heat must be dissipated. This can be ameliorated by spraying with cool water. In new designs the problem can be handled by using larger conductors to reduce heat generation, selecting insulation such as Teflon with high heat resistance or designing a winch system that is adequately cooled with water.

The effects of weather conditions and changes in conditions on the ROV crew must also be considered. Individuals and supervisors must be alert to such extreme effects as heat stroke, heat exhaustion and frost bite, as well as to such relatively minor effects as sunburn, chill, seasickness and the general discomfort from heat and cold that affects individual performance. The possible effects of extremely cold temperatures on ROV operations are discussed in the Arctic section later in this chapter and in Appendix G.

Foul weather (i.e., wind, rain, snow, sleet, etc.) can make working on deck vary from the usual dangerous up to treacherous. Occasions will arise that will require crewmembers to risk safety in order to accomplish tasks, or at least, to think they should or must risk safety. Recovering an ROV in heavy seas caused by high winds with rain, for example, can cause a person to lose perspective. The feeling of urgency under severe conditions must be controlled so as not to interfere with good judgement. A mistake or slip during good weather conditions may be embarrassing, but under bad weather conditions it can be deadly.

Water Characteristics

The characteristics of the medium in which tethered, free-swimming ROVs operate can influence the user's selection of the proper vehicle for a given job as well as the effectiveness of job performance. Visibility, buoyancy, sound propagation and degradation of the materials from which the vehicle and its connecting cables are made are all important in the selection process. The water characteristics are best identified and described through measurements of its optical properties, temperature and salinity (electrical conductivity). Each is discussed in the following sections.

Optical Properties

Optical systems play a major role in the operation of ROVs, which have built their usefulness on closed circuit television, where many of them are simply a means for placing a camera in a useful location. Television viewing provides the simplest means for piloting the vehicle when observation of the condition of a site or the presence of a particular object may be the system's primary mission. The ability to see controls the selection of manipulating devices and the effectiveness with which they can be used. It also effects photography, which constitutes a major part of the documentation of survey and search operations. Low visibility can slow operations drastically or even dictate the use of more sophisticated equipment (e.g., acoustic imaging system, laser line scanners, or more complex illuminating geometries).

Three important optical factors controlling all these functions are light refraction, absorption and scattering. For nearly all practical ROV operations, the variations in refractive properties, which occur naturally in both fresh and salt water, can be neglected. The variations of absorption and scattering, however, can be very large and are the major contributors to degradation of system effectiveness, both by attenuating the actual transmission of light and by degrading image contrast. The two simplest direct measures of optical properties are beam transmission and backscattering. In even the clearest seawater, the attenuation length will not exceed about 65 feet and usually in near surface environments it will be substantially less. The primary degradation occurs because of scattering of light by suspended materials (sediment, biological materials and bubbles) and thus will be closely tied to weather conditions that cause substantial local water motion and, in some instances, can reduce visibility to essentially zero.

Operation of the vehicle near the bottom can also cause problems by stirring up fine-grained sediment. This is especially critical in low or zero current situations. These factors are all treated in a variety of texts on optical oceanography and underwater photography and are discussed in more detail in Chapter 6 – Underwater Viewing Systems.

Temperature

Temperature affects ROV operations in several ways. The components most affected are electronics, umbilicals, hydraulics/lubricants and structures. Vehicle positioning is also affected by thermoclines and differences in salinity and there are some second order affects such as that on buoyancy. However, it is for the primary temperature effects that plans must be made when operating in conditions where there is:

- Hot Air & Warm Water—Tropics
- Frigid Air & Cold Water—Arctic
- Warm Air & Cold Water—Arctic
- Warm Air & Cool Water—Temperate Coastal Zones with upwelling

Either extremes of cold or heat may affect electronics. Most present day electronics are able to handle tremendous temperature extremes. Occasionally, when a component is deteriorating or is improperly heat-sinked, the electronics may become unreliable after a fixed period of operation. This is most often a high temperature phenomenon that can often be detected by passing a heat gun over the suspected electronics.

The effect of temperature extremes on structures can be very serious if there is an abrupt change, as there would be when launching a vehicle from the deck at -40^{o}C (-40^{o}F) in the Arctic into 0^{o}C (32^{o}F) or warmer water. This thermal shock can cause materials to fracture. Thus, in northern climates, some judgement should be used in slowly warming a vehicle before launching.

ROVs are so portable it is not unreasonable to expect a vehicle to be moved from very warm to very cold operating theaters in a short time. For this reason, hydraulics and lubricants should be selected so they have only a modest change in properties over a large temperature range.

With the obvious fact that freezing precludes the existence of in-water temperatures substantially below 0^{o}C (32^{o}F), most ROV systems are designed with 0^{o}C (32^{o}F) operations in mind. One must therefore be careful, especially when using them in the occasional, localized high temperature zones. These zones can occur in reasonably large captive water bodies (e.g., lagoons) where temperatures may rise to 50^{o}C (122^{o}F), in hydrothermal brine pools, e.g., 100^{o}C (212^{o}F) in certain Red Sea areas. And, in spreading center hydrothermal zones, temperatures exceeding 350^{o}C (662^{o}F) have been reported at 8,200-ft (2,500-m) depths, albeit in very localized plumes, which produce negligible effects even one or two meters away in the horizontal direction.

Temperature effects on buoyancy are usually only noticeable in ROV operations near the thermocline. It may be necessary to ballast heavy relative to warm surface waters in order to be able to thrust down through the density gradient at the thermocline and operate in the cooler, more buoyant, water below. It is even possible that a vehicle, ballasted to be a few pounds positive at depth, can break from its tether and rise only as far as the thermocline rather than coming all the way to the surface. In one instance, an autonomous vehicle being recovered under emergency conditions rose only to the thermocline where it remained. An ROV was used to grab the vehicle and pull it through the thermocline to the surface for recovery.

Since sound propagation speed is directly related to temperature (higher temperature = higher velocity), gradients in the temperature will lead to refractive effects that can produce shadow zones near the sea surface. These will not be particularly noticeable for short-range sonars or those that operate using near vertical paths, but may be apparent if transponder navigation is being used with long, near-horizontal paths.

Salinity

Salinity is best measured *in situ* by measuring the electrical conductivity and temperature of the water and, thus, its variability is often equated with the variations of this prime electrical quantity. Since nearly all ROVs are designed to operate with non-grounded power supplies, the effects of conductivity are limited to three. First is the fact that sea water will act as the electrolyte for localized cells in which the electrodes are dissimilar metals in the vehicles. This is the primary cause of corrosion and is the reason for deliberately installing sacrificial materials (zinc, magnesium) on vehicles. These precautions would not be necessary in fresh water operations. Second, is the fact that any exposed wiring that has defective insulation leads to immediate grounding of that part of the circuit and to short circuits if more than one such defect exists. Third, which is the only positive aspect of conductivity effects, the ocean provides good electrical shielding from electromagnetic noise sources and, thus, vehicle electronics may perform better in water (saltwater) than in air.

Water density is also related to salinity. Most vehicles are designed with normal seawater density in mind. The gradients encountered in the ocean will generally be negligible operationally, except in three very important environments. Near river mouths, operations in estuarine environments with appreciable tidal flow, and in the vicinity of sewer outfalls where one can have trouble with substantial, time-varying buoyancy changes. While these usually cannot be known in-detail, they can be anticipated and the operator can realize that it may even be necessary to retrieve and re-ballast the vehicle or include remotely controlled ballast alteration means. Ice can also provide a localized source of fresh water that can produce noticeable buoyancy effects.

Pollutants

In addition to the properties discussed above, water (salt or fresh) is a good medium for carrying other ingredients, in either dissolved or suspended form. Some of these can be of concern to the ROV operator or designer. Given their orientation to oil field use, it is clear that ROVs may encounter either natural or man-made petroleum derivatives. These can cloud camera lenses and even lead to deterioration of some plastic materials (e.g., Lexan). Gasses in the water may originate as air bubbles swept down from the surface, from diving or compressed air tool use, or they may be of natural origin seeping from the bottom. These can have obvious effects on visibility, but one should also anticipate sudden drastic losses of buoyancy through aeration of the water. Bubbles also are very effective in blocking sound transmission and reflecting sound in ways that can seriously degrade sonar performance. Fortunately, most of these effects are associated with discrete sources and, therefore, it is usually possible to track their locations acoustically and work around them.

Finally, there are special areas in which more highly corrosive environments may be encountered. Brine pools, hydrothermal springs and sewer outfalls all should lead the operator to take special precautions that will vary depending on the nature of the materials used for in-water portions of the system.

Bottom Characteristics

On a global scale, the ocean bottom has as great a topographical variety as does the landmass surface. Sea bed topography varies from gradual slopes of continental shelf areas, to vast desert-like plains of the deep ocean, to subsea mountain ranges with peaks higher than Mt. Everest. While ROV operators should be generally aware of these global variations, operators of tethered, free-swimming vehicles should be more concerned with more localized, site specific topographical variations.

Localized bottom characteristics such as rock outcroppings, hills and valleys, soft or silty bottoms, and bottom currents can all affect the successful operation of an ROV. For instance, multiple rock outcroppings will increase the chance of collision damage to the vehicle and the cage (if used). They also increase the possibility of abrasive damage or entanglement of the vehicle's tether. Furthermore, rock outcroppings, coral heads, cliffs or hills can all impair the ROV operator's "visibility" by blocking out video or sonar visibility.

Operating over a soft or silty bottom can cause difficulty to ROV operations because the bottom can be unintentionally stirred up by the ROV landing heavily on it or by its thruster use, particularly upward or astern thrust. The resultant debris can remain for long periods of time if there is no current, thus precluding operations. Operations can be facilitated by:

- Applying even forward power to the vehicle when the bottom reflection of the lights is first observed (and at the same time slowing the descent)

- Working into the current or across the current where practical, so that the currents clear your vision. Where the condition is not serious, visibility can sometimes be improved by operating thrusters ahead when the vehicle is sitting on the bottom, thus pumping water through the vehicle to clear visibility

- Flying the vehicle slowly ahead out of the cloud on a fixed heading when there is no risk of entanglement

In certain operations it may prove advantageous to the operator to set the vehicle cage (if used) on the bottom and fly the vehicle out from that position. In such a case it is very important to have a good understanding of the bearing strength of the bottom. If the bottom conditions were too soft and the cage sank into it, some unusually high loads could be placed on the umbilical when it came time to lift the cage off the bottom.

In general, all of these potential problems increase the difficulty in maneuvering the vehicle safely and thus highlight the need for experienced operators. Also, it becomes evident that it is advisable to try to know as much as possible about the expected bottom characteristics before embarking on a given operation.

Arctic

Operational experience with ROVs under Arctic conditions is sparse relative to other ocean areas, but with operations such as that performed by ISE’s Theseus, the data is increasing. The experience that has been gained points to one fact: things that work well in warm climates–unless properly adapted–typically either don't work or will break in the Arctic. Since Arctic logistics problems are unique and fierce, equipment and parts redundancy is essential.

The existence of ice and severe cold temperatures pose the most significant problems to ROV operations. Ice can be a double-headed axe. On the positive side, it can reduce sea state to virtually zero and, at the extreme, provide the mariner the unique opportunity of driving to the work site. It can also serve as a free-of-charge, stable support platform. On the negative side, excavating a hole through 6 to 10 ft (1.8 to 3 m) of ice is time consuming and not always easy. The hole must be maintained ice-free and the stable, but mobile, platform can migrate as much as 13 nm (24 km) in 24 hours. Also, where the ice is in the form or bergs and pancakes, a great deal of effort must be placed on maneuvering to avoid the risk of cable entanglement.

The cold of the Arctic (and the sub-Arctic) significantly hampers human activity and promotes major problems in the operation and maintenance of equipment and machinery, a situation that can be compounded by winds and precipitation. Cold temperatures preclude the use of many conventional pieces of equipment, materials and procedures.

Extremely low air temperature can also cause ROV system and equipment problems. These temperatures would include extended exposure to temperatures below freezing and shorter-term exposure to temperatures from -20^{o}C to -40^{o}C (-4^{o}F to -40^{o}F) and lower. A change in temperature from -40^{o}C (-40^{o}F) air temperature to seawater between -2^{o}C and 0^{o}C (28.4^{o}F and 32^{o}F) is a significant change. Sudden emersion of an ROV without consideration of this change could easily result in flooding due to shrunken, cracked or loose components or connectors.

The effect of still air at extremely low temperatures can be greatly increased and exaggerated by wind chill. Plastic and rubber materials can become very brittle when subjected to extreme low temperatures. If not carefully handled, stored and protected under these temperature conditions, such materials can be easily broken or cracked. Circuit boards, edge connectors, underwater molded epoxy connectors, component mounts and retainers are all subject to damage or loosening.

After storage or transport at extreme low temperatures, an ROV system should be thoroughly examined and checked for damage. Truck rides or other land transport over short or long distances on rough winter roads can cause severe vibration that may be especially damaging at low temperatures.

A system should be rewarmed slowly after long periods at extreme low temperatures. This can be accomplished by moving the system into a relatively warm area for storage for 12-24 hours prior to use. All crates and containers should be opened to allow good air circulation in and around system components.

In extreme low temperature environments, stratification of air can occur within storage and operations shelters and enclosures. Simply having an item or component inside a warmed area may not protect it. A difference in temperature of as much as 16^{o}C to 38^{o}C (61^{o}F to 100^{o}F) could exist from ceiling to floor inside a temporary enclosure in the Arctic. This may not be realized by a technician wearing Arctic boots and protective clothing, but a video recorder, video tape or film, for example, would protest severely if taken from a storage location on the floor at -28^{o}C (-18.4^{o}F) and be expected to function immediately when placed on an elevated instrument rack at head or shoulder level where the temperature is 21^{o}C (70^{o}F).

Although humidity is not usually a problem under Arctic conditions, condensation and frosting can and will occur when equipment is moved from one temperature environment to another. Anticipation of this problem by allowing adequate time for temperature adjustment and climatization will provide a solution.

Lubricating oils and hydraulic fluids that work well at 38^{o}C (100^{o}F) in the tropics will flow like molasses at extreme low temperatures. Also, a hydraulic unit that is filled with thin fluid anticipating exposure to low temperature operation, which is then enclosed and heated, may operate hot and lose pressure and power.

Another aspect unique to the Arctic is the great range of temperature that can exist between the air and seawater. Some of the results of this thermal anomaly are discussed in the previous section on temperature. The Arctic is an area that is looming larger and larger into our future. There is also potential that the Arctic will be a major offshore oil and gas-producing region in the future. Although there is a great deal published concerning the Arctic environment, to obtain this data takes some time and a well-equipped library. In view of this and to prepare the potential Arctic ROV operator, a section has been included in Appendix G that highlights the Arctic environmental conditions.

Biological Environment

Although the vast majority of ROV operations are not concerned with operating difficulties posed by characteristics of the biological environmental, there are several areas of potential impact that should be mentioned.

In some of the shallower coastal areas, forests of kelp can be encountered. Two potential difficulties arise from operating within a kelp-infested area. First is the obvious problem of visual (video and sonar) impairment. Second, the high potential for entanglement. In the latter, tether entanglement is one concern. Of equal importance is the potential for ingestion of kelp by the vehicle's thrusters, thereby immobilizing them. The accumulation of kelp on the vehicle's tether can increase drag on the system and cause equipment fouling during recovery.

Another potential impact on ROV operations would be operating in areas of large fish populations. Sonar search operations may prove to be futile due to the fact that the air bladders in fish produce tremendous backscatter on sonars.

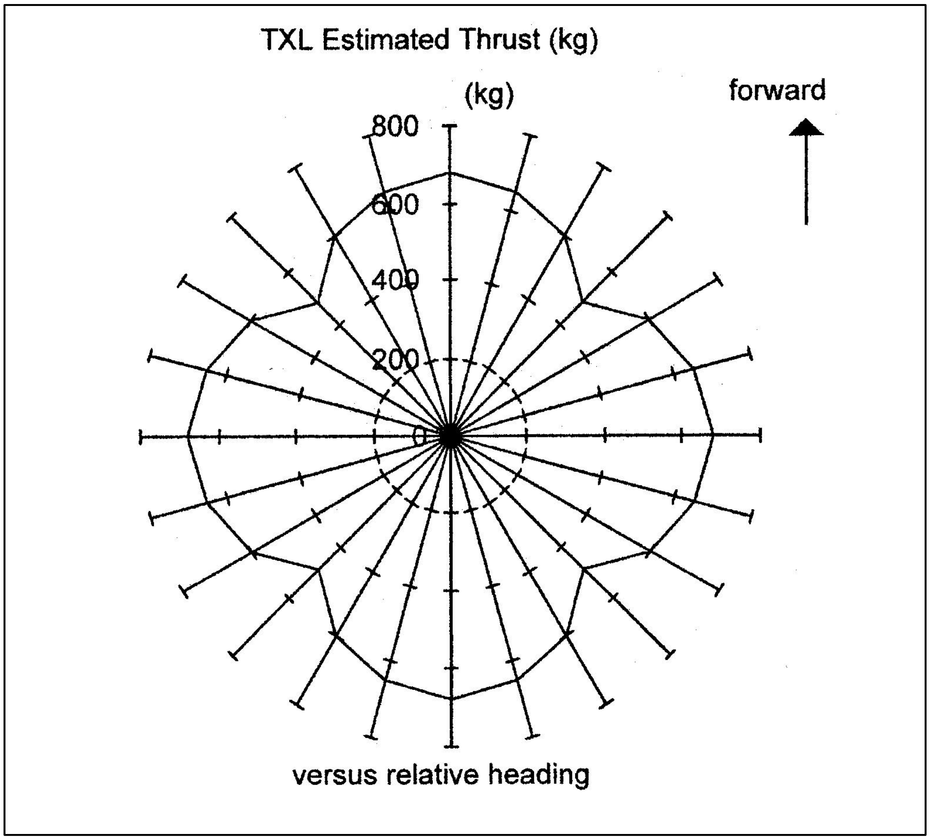
Sharks and other large predatory fish may also present problems to ROV operations. Mooring cables and lines are often attacked and have sustained, in many instances, substantial damage. Even underwater fiber optic cables and microcables have experienced fish bite failures.

And, as discussed in the section on inland operations, using ROVs in some situations can mandate significant decontamination procedures.

ROV OPERATIONAL FOOTPRINT AND SPEED

The performance of an ROV is dependent upon many factors including thrust capability, vehicle speed, vehicle drag, tether drag, umbilical drag (if not a caged vehicle), current and current direction. As an example of ROV performance, the Perry Tritech *Triton XL* is examined.

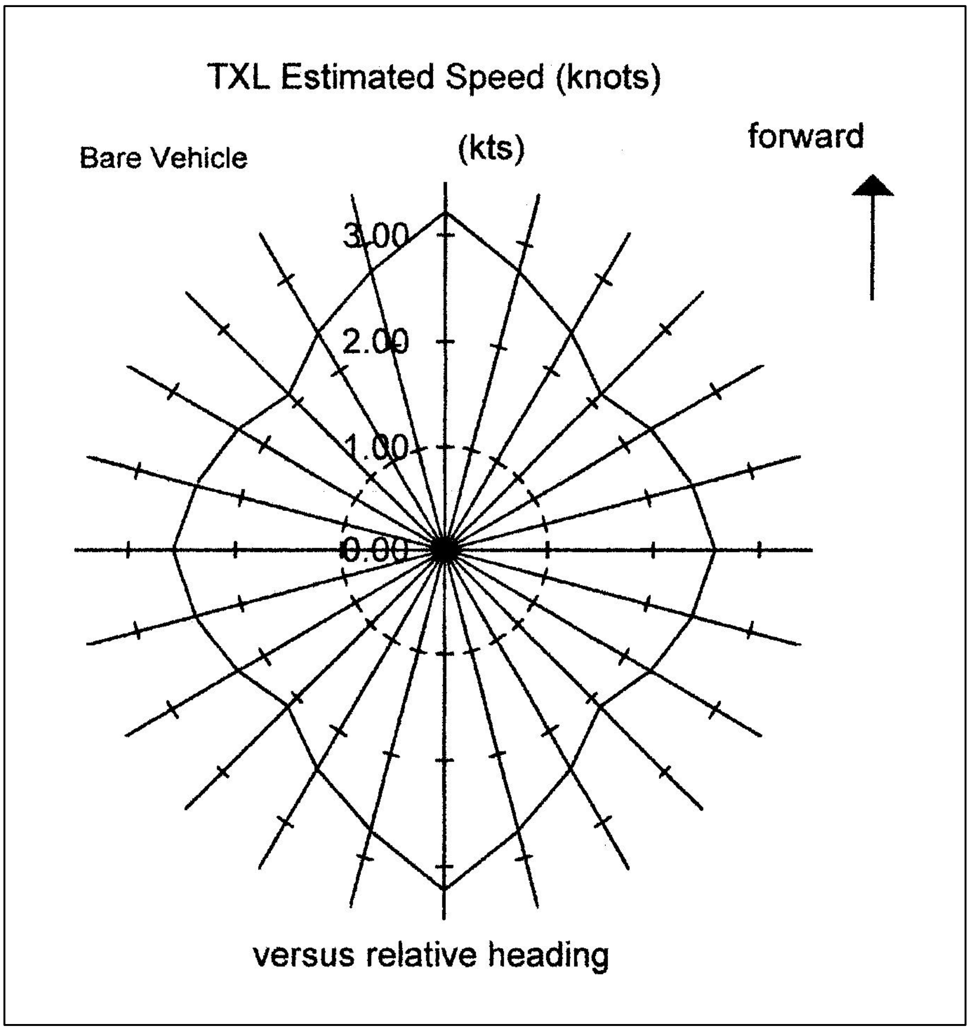
In the following diagram, the *Triton XL*'s thrust performance is given for a bare vehicle (no work packages) vs. its relative heading.



Thrust vs. Relative Heading for *Triton XL*
(Perry Tritech)

In a similar manner, the speed of the ROV can be illustrated by looking at the *Triton XL's* estimated speed vs. relative heading. In the next diagram, it can be seen that the highest speeds attainable are in forward and reverse direction due to the lower drag area of the ROV. When translating sideways at various angles, the speed varies due to both drag and thruster position (efficiency).

For vehicles that use tether management systems, only the drag of the tether comes into the equation in the performance envelope. Ultra-deep ROVs that use only an umbilical (cageless) normally have a very small footprint due to the high forces required to overcome the drag on a long, large diameter umbilical. In designs where a Kevlar umbilical is used, a depressor is sometimes used instead of a cage to allow the vehicle to have a working footprint after the depressor hits the bottom. Regardless of the method used for getting an ROV to very deep depths, i.e., >20,000 ft (6,096 m), using the vehicle to move about an area is difficult at best. The ship and the vehicle must work in unison since the "plumb bob" vehicle will have to wait for the cable/ship combination above to move through the water column. In some cases where a TMS has been used, thrusters have been added to the TMS to increase the mobility of the ROV.



Speed vs. Relative Heading for *Triton XL*
(Perry Tritech)

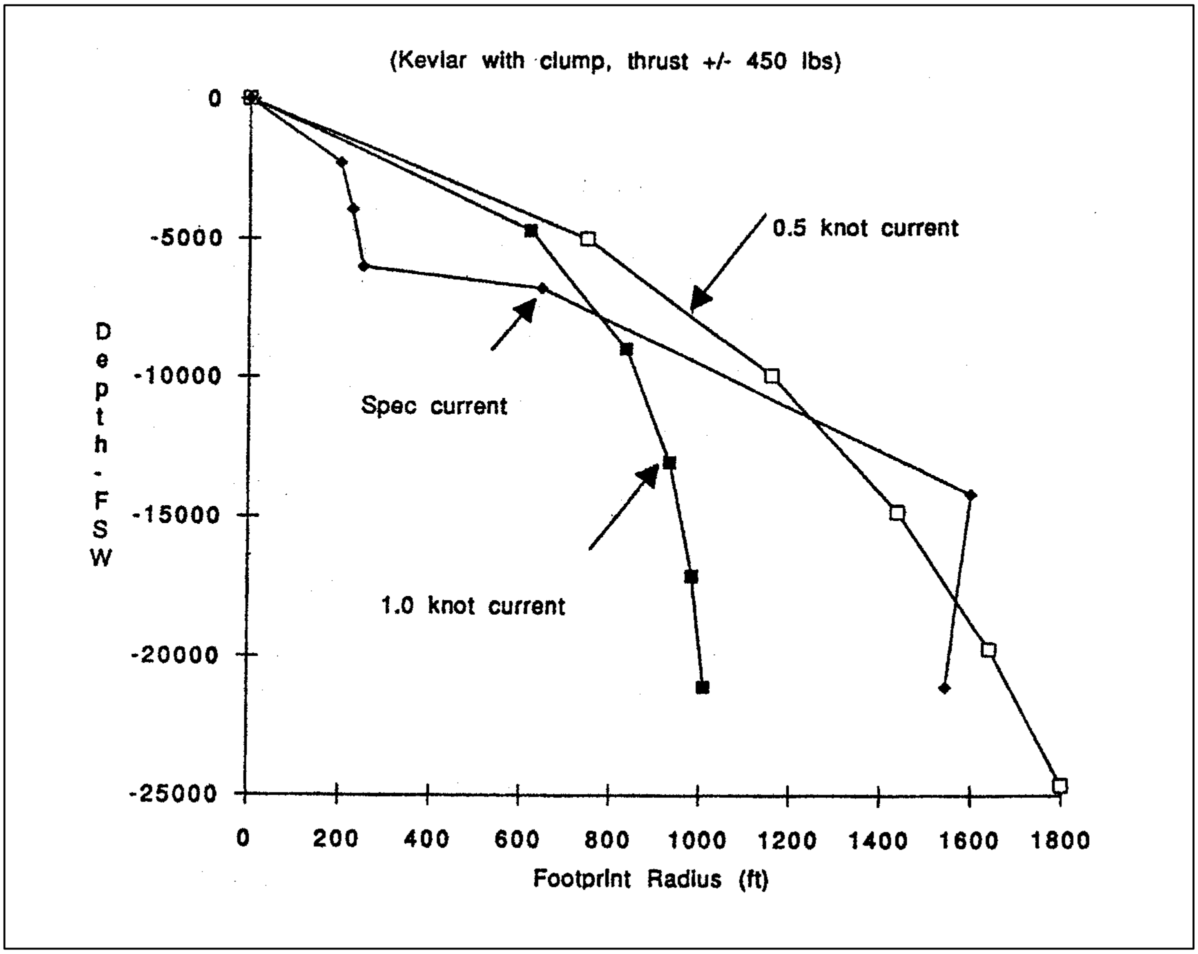
The effects of current on an umbilical can be seen in the case where an ROV system has a 25,000 ft (7,620 m) long Kevlar umbilical in a 3.0 kt (5.6 km/hr) current to 6,000 ft (1,829 m) and uniform current of 0.5 kt (0.9 km/hr) to 20,000 ft (6,096 m). In order for the vehicle to reach the bottom, a 2,000-lb (907 kg) clump weight or TMS would be required and, due to the catenary in the cable, the ROV would touch down 9,000 ft (2,743 m) downstream. For the same vehicle using a steel armored cable, the ROV would be located about 3,000 ft (914 m) downstream.

Obviously, many tradeoffs exist that determine the selection of the vehicle umbilical, some of which are:

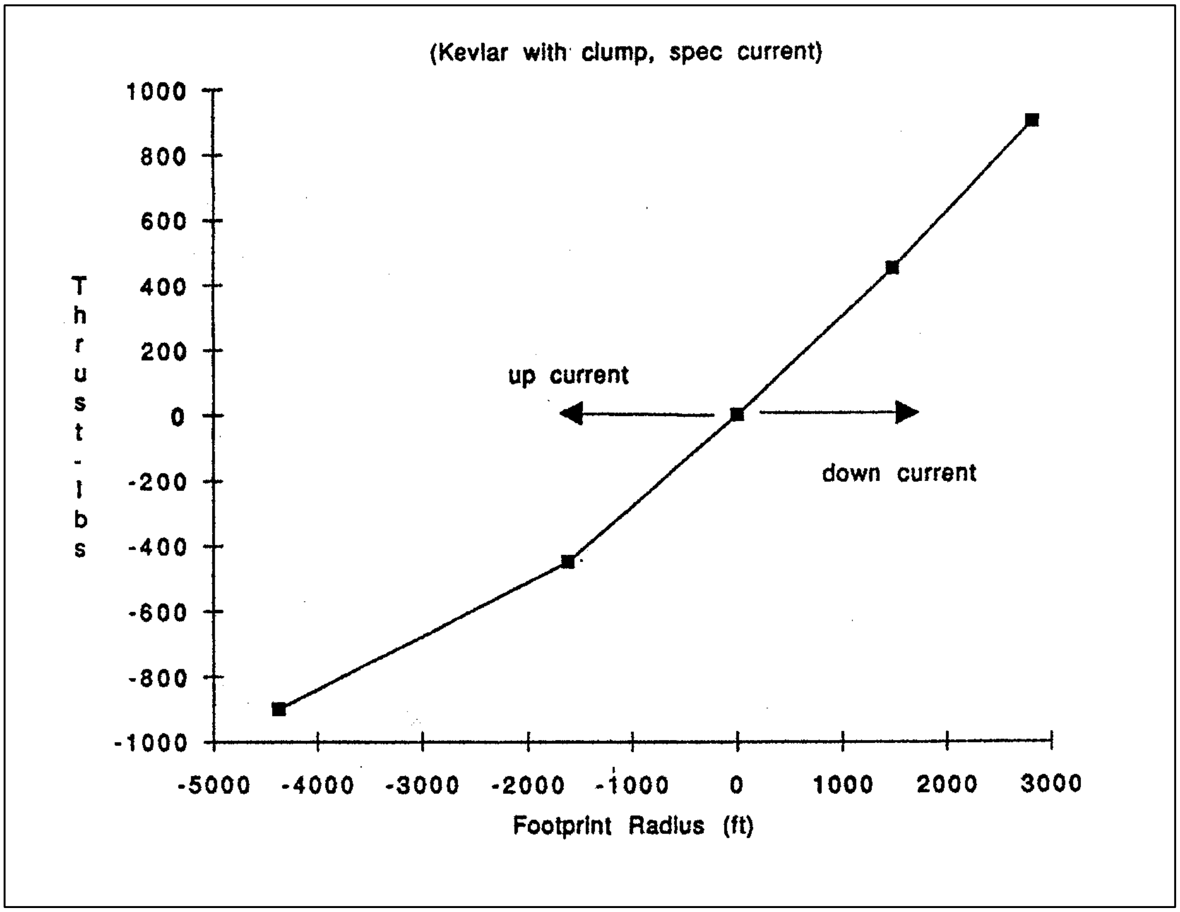
- Current profile
- Water depth
- Cable strength
- Cable Diameter
- Power down the cable
- ROV thrust capability
- Cable on the winch drum (heating)
- Cost

For ROVs that operate in both shallow and deep water, two different umbilicals are sometimes employed. Other considerations regarding umbilical design are handling equipment. A 25,000 ft (7,620 m) long steel umbilical requires the topside winch and crane to have a strength three times greater than a comparable Kevlar cable would require. This would mean that more deck space and strength would be required.

Typical displays of footprint vs. depth and thrust are shown on the following pages for a hypothetical ROV.



ROV Footprint vs. Depth
(Perry Tritech)



ROV Footprint vs. Thrust
(Perry Tritech)

FABLES AND OTHER DREAMS

It was originally intended to provide a more expanded discussion of limitations of ROVs in this section, however, upon completing most of this publication, it became obvious that the reader should have an excellent understanding of just what such vehicles can and can not do. However, there are just a few items that should be highlighted.

Raise the *Titanic*

The *Titanic* will, contrary to many TV movies and other dreamers, remain on the bottom. TV documentaries, where small pieces of the sunken liner were brought to the surface, just lend substance to that comment. As broadcast around the world, getting a piece of the wreck to the surface is only part of the problem; designing the total recovery system to get it through the sea-air interface is the other, and often hardest, problem. Now, smaller ships have been recovered intact from shallower waters, but that has been with the assistance of gigantic crane barges or other equipment. And, wreckage, including entire aircraft and helicopters, has been brought up from the deepest depths–as shown in other sections of this publication. These successes were brought about through extensive planning and preparation by deep-sea recovery experts using the most advanced equipment and techniques. The point here is that today's ROVs, when used by those knowledgeable in the business, can recover a wealth of material from the ocean bottom. Unfortunately, there are limits. One of them is the Titanic, and other similar ships, will remain on the bottom. RIP!

The Manipulators of Petaluma

"My manipulator can beat your manipulator!" This is a statement more likely heard in the aisles of underwater conventions, rather than at the arm wrestling championships held annually in Petaluma, California. As highlighted in this publication, the manipulators are becoming exceptional robotic devices. Schilling, Slingsby, Kraft, and others are producing an exceptional array of manipulators and grabbers, with many models surpassing the century mark of fielded systems. More reliable, stronger–they are impressive. With names like Conan, Titan and Predator, one would expect nothing less. Designs like Schilling's Conan look like they morphed from Arnold Schwarzenegger or the beast from the movie Alien.

Unfortunately, they are not to the level of performing underwater soldering, disassembly and disarming of mines, self repair, fish surgery, or any other futuristic task that is often seen in the movies, or in the laboratory being performed by highly intricate systems. And, unlike the movies–or on land–giant claws are not likely to be seen underwater, carrying around large submersibles and other huge structures. Why? Unless what you are carrying is neutrally buoyant, you have to consider the weight to counterbalance the load and design an interface with the seafloor that will prevent the device from burying itself.

The answer, finally being seen in the offshore industry, is properly designed systems. Systems that are established with underwater work and maintenance in mind. Systems where advanced tools are developed for remote intervention and systems where the very capable manipulators being produced today can perform the tasks that are within their rather limited range of operation–limited when comparing their capability to the massive task of working on subsea completion systems. Systems integration and advanced planning is omnipotent, and finally here. Well, it has always been here; the difference is–now it is being applied. The result will be deepwater remote intervention by ROVs with manipulator and tool systems that can properly perform the task assigned.

Will Conan ever challenge Predator in Petaluma? Unlikely, but I'd pay the price of admission to the next Underwater Intervention conference to see such a one-on-one competition. The World's Underwater Manipulator Arm Wrestling Championship. Why not?

Don't Shout Stealth!

One of the major concerns with ROVs is the noise they produce. This problem can just be acoustic, or in the area of mine countermeasures, it can cover magnetic, electro-magnetic, or other concerns. There are even vehicles on the market today with the name *Stealth,* which may or may not live up to this title. The problem is that underwater hydraulics and electrical systems make noise, and that is not easy to eliminate or mask. Water is an excellent conductor, and you can bet that if you generate noise underwater–ragardless of the type–it will reach an object that you would rather it didn't. Unfortunately, the laws of physics are still the laws of physics. And, regardless of what many marketeers say, there is no such thing as a totally quiet ROV.

For the area where acoustic signals are sent into the water, the adverse effect will revolve around their interference with other such equipment. Thus, this is a design problem that can be addressed in the beginning of the overall system design. Assuming you're not working in a minefield, the problems can usually be controlled.

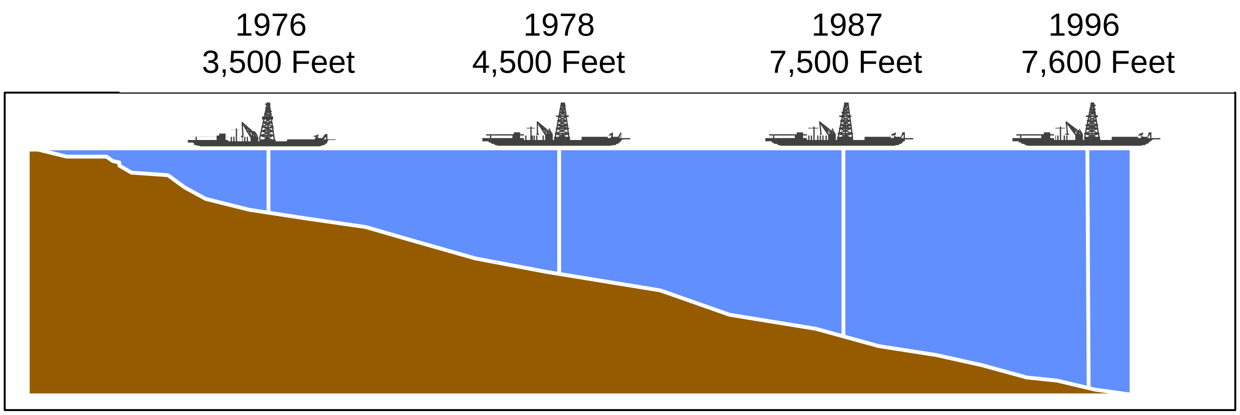
The US Navy has spent a fortune on quieting techniques for ships, submarines, and undersea vehicles. The Mine Neutralization System, the most expensive MCM ROV on the market, has never fully realized the original stealthy goals of its developers. New programs such as the LMRS will have an even harder problem when they have to miniaturize the technology to operate from a submarine torpedo tube.

The bottom line is that there is both good and bad news. The bad news is that if you want to have a stealthy system, you can plan on spending a lot of money, with no guarantee that you will reach your goals. The good news is that, as in the case of many ships, every ROV can be a successful mine hunter–at least once.

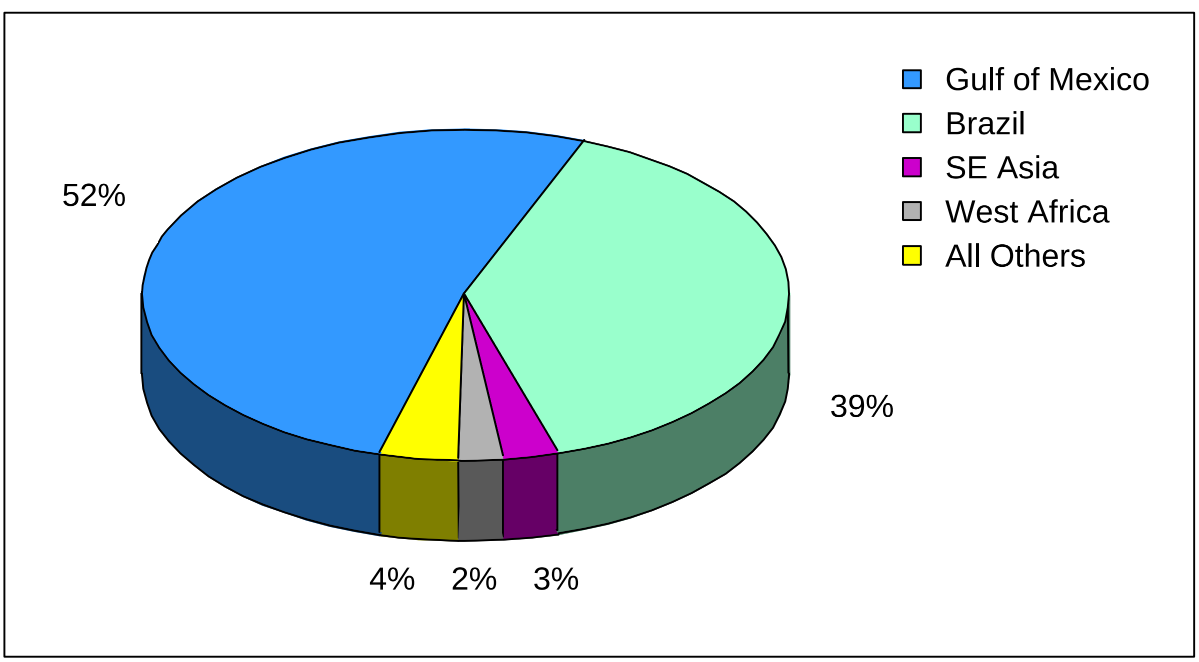
CHAPTER 4. WHERE ARE THEY DOING IT?

EXPLORATION WATER DEPTHS

Tasks for ROVs in support to deepwater pipelines, and other tasks, continues to increase in both depth and complexity. As shown in the figures below, the exploration water depths in the Gulf of Mexico have more than doubled during the last two decades, increasing from depths of 3,500 ft (1,067 m) in 1976 to 7,600 ft (2,316 m) in 1996. Drilling in the Gulf of Mexico and off Brazil in depths beyond 3000 ft (914 m) accounts for over 90 percent of the worldwide effort between 1985 and 1997. And this trend is not expected to decrease in the future.

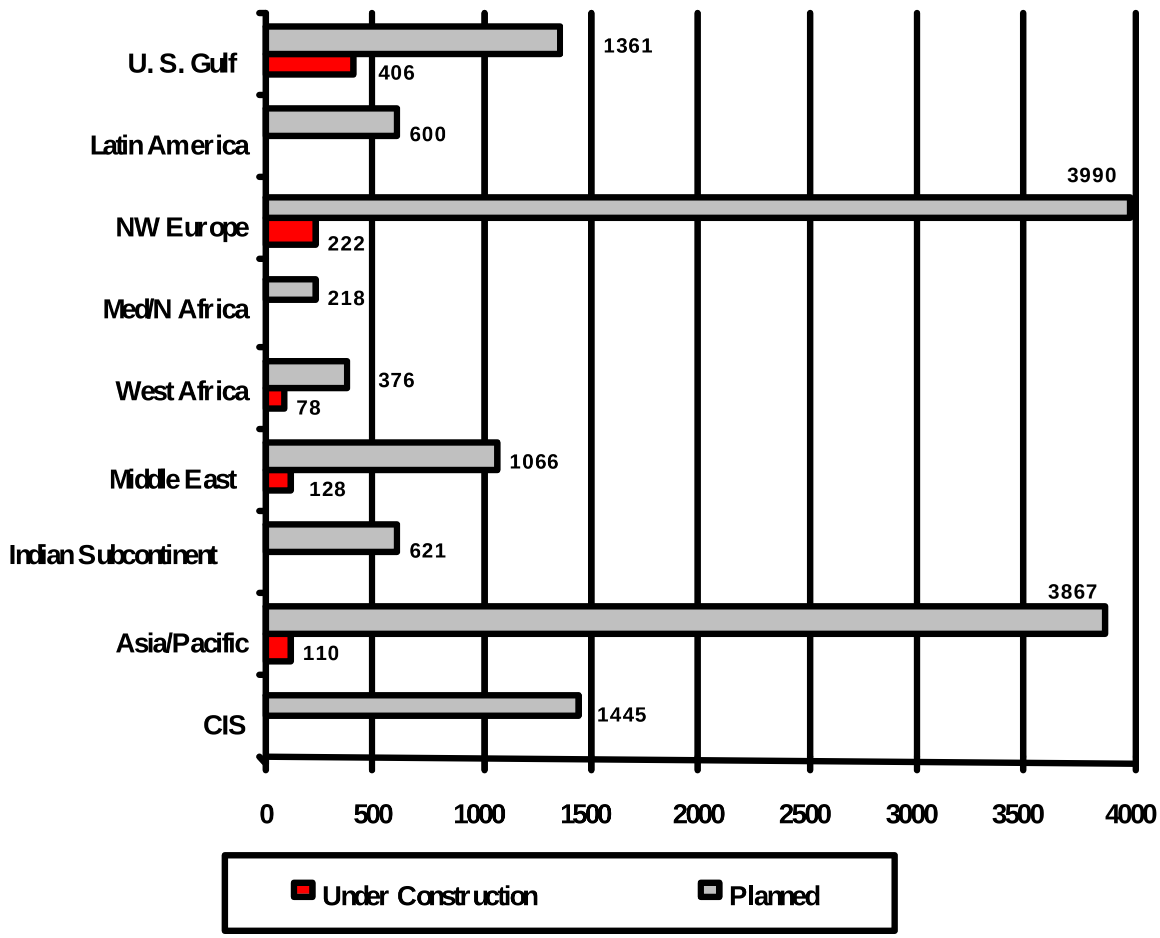


Gulf of Mexico Drilling Milestones



3000+ Foot Wells Drilled Worldwide (1985 – Oct 1997)

When considering the pipeline mileage that will be installed in the future to support offshore drilling, this category of ROV support becomes even more impressive. As shown below, there are 944 total miles (1,519 km) of pipeline under construction. An additional 13,852 miles (22,288 km) are in the planning stages. No mater how you look at those figures, it bodes well for operators who will be installing and maintaining such hardware.



World Wide Pipeline Mileage
Planned and Under Construction 1996+
(Subsea Pipeline Technologies for Deepwater
IBC Conference, December 1997)

ROV OPERATIONS

The move into deep water for oil and gas exploration, development and production has opened up a whole new market for innovative solutions to operating systems on the seabed. The world's largest offshore developments (*Offshore Magazine, 1997 International report, May 1997*) are currently in Saudi Arabia (Persian Gulf), Gulf of Mexico, the North Sea, Malaysia (S.E. Asia), and India (Arabian Sea) along with West Africa and the South China Sea current "hot spots". According to a January,1998 forecast in *Sea Technology* magazine, governments in the United Kingdom, Norway, Denmark, Ireland, Angola, Cameroon, Gabon, Egypt, Namibia, Senegal, Trinidad and Tobago, Australia, Bangladesh, and Cambodia are among those that will be offering licenses in 1998.

Exploration is already being carried out in water depths over 10,000 ft (3,048 m), while production is quickly approaching this depth. The move into deep water, in the US Gulf of Mexico alone, has created a new regulatory problem that is only beginning to be addressed by agencies like the Department of Transportation (DOT), United States Coast Guard (USCG), the American Bureau of Shipping (ABS), the Mineral Management Service (MMS) and others. All of these agencies are now faced with the problem of safety to personnel and safety of the environment as technology attempts to keep pace with new discoveries in deeper and deeper water. Regulations exist in locations such as the North Sea, under the watchful eye of Det Norske Veritas (DNV) and the governments responsible for the sectors being developed. The need to monitor this activity in the US, and in other areas around the world, will be critical in the prevention of a disaster to life or the coastal environment.

There are several spots around the world where the majority of ROV operations occur. They are tied, of course, to the production of oil and gas. It is estimated that there are nearly 400 work class ROVs in operation at his time servicing the oil and gas industry. The following sections will address their level of activity around the world.

Europe

The North Sea has always been an area of high ROV activity with systems being operated in both the UK and Norwegian Sectors. The majority of operations in the North Sea are in water depths of 492 ft (150 m) or less. Recently, there has been a move to West of Shetlands, designated a "frontier" area where the water is much deeper–1,148 to 3,281 ft (350 to 1,000 m)–and wind and current conditions more severe.

- Norsk Hydro is drilling wells in water to 3,937 ft (1,200 m) in the Ormen Lange area.

- Geoteam is performing surveys of the continental margin in water up to 15,748 ft (4,800 m) deep.

- BP Norge is drilling on the Norwegian shelf in 3,937 ft (1,200 m) of water.

- Norway has drilled its deepest well in 4,180 ft (1,274 m) of water and they have discovered gas at 12,795 ft (3,900 m) in the Voring basin.

It is believed that one of the largest concentrations of ROVs is in this region with over 100 systems in operation.

Asia

Much activity stretches from Western Australia (Asia Pacific) to Malaysia and the South China Sea.

- Woodside Offshore Petroleum is beginning developments in up to 1,312 ft (400 m) in the Timor Sea.

- Mobil and Texaco are conducting seismic studies in the Gorgon field of Western Australia in 2,953 to 5,249 ft (900 to 1,600 m) depths in search of additional natural gas reserves.

According to a report from Mackay Consultants, expenditures in this region in 1999 could exceed those of northwest Europe and may reach 21.8 percent of the world's total being spent on offshore oil and gas developments.

South America

The overwhelming majority of ROV operations in South America are occurring off Brazil and mainly in the oil rich Campos Basin. Petrobras continues the race to deeper water in the Campos Basin in up to 6,562 ft (2,000 m) of water.

- Petrobras' Marlim South development currently holds the record for the deepest onstream well at 5,732 ft (1,747 m).

- Petrobras also has Roncador waiting at a depth of 6,020 ft (1,835 m).

Now, with the deregulation of oil operations off Brazil, many new companies are moving in with ROV systems to support the expected increase in oil production.

North America

The latest round of leasing has resulted in the largest bid ($825 million) ever for exploration in the Western Gulf of Mexico in water over 6,562 ft (2,000 m) deep. The Minerals Management Service (MMS) has reported 104 deepwater prospects in water deeper than 9,843 ft (3,000 m) and 31 rigs simultaneously drilling in these deepwater regions. The MMS has also estimated that as much as 35 percent of the production in the Gulf in the year 2000 will be in deep water, up from a mere 4 percent in 1995.

Between 1987 and 1997, the number of operators in the Gulf has increased from 77 to 157.

A listing of the most significant offshore developments in the Gulf follow:

- Shell has multiple deep water projects including Ursa – 4,035 ft (1,230 m), Auger – 2,953 ft (900 m), Tahoe – 1,837 ft (560 m), Mars – 3,002 ft (915 m), Cardamom – 3,094 ft (943 m), Glyder – 3,392 ft (1,034 m), Ram-Powell – 3,287 ft (1,002 m), Mensa – 5,518 ft (1,682 m), Marconi – 3,881 ft (1,183 m), Angus – 2,096 ft (639 m) and Europa – 4,091 ft (1,247 m). Overall, Shell has 14 deepwater developments in the Gulf.

- Fugro is performing geotechnical investigations in 5,582 ft (1680 m) of water.

- Oryx Energy has installed Neptune, the world's first production spar, on Viosca Knoll in 1,942 ft (592 m).

- Texaco has Gemini 3,468 ft (1,057 m) and Fuji 4,337 ft (1,322 m).

- Global Marine is converting the *Glomar Explorer* for drilling in over 9,843 ft (3,000 m).

- Allseas and Global Industries have installed the pipelines for Shell's Auger, Mensa and Ram Powell developments in water to 5,518 ft (1,682 m).

- Exxon has the Diana project in over 4,593 ft (1,400 m) of water, the Rockefeller in 5,102 ft (1,555 m), Mickey in 4,350 ft (1,326 m) and their Hoover prospect in 4,800 ft (1,463 m).

- Shell, Amoco, Mobil and Texaco have begun drilling exploratory wells in over 7,972 ft (2,430 m) of water in Alaminos Canyon.

- Several other fields are planned in deepwater, including Shell's Baha in 7,792 ft (2,375 m), which will continue to require increased ROV support.

- Conoco Inc. and Reading & Bates Corp. have teamed to develop blocks located in depths ranging from 1000 to 9,000 ft (305 to 2,743 m).

It has been reported that there are nearly 70 work class ROVs in operation in this region, which is expected by some to reach 100 by the end of 1998. The table on the next page provides a survey of recent and projected deployment of work class ROV systems by Gulf contractors, which supports this projection.

Gulf Coast Based ROV Contractors
(Work Class ROV Systems)

	7-20-98	4-1-99
CalDive International	2	2
Canyon Offshore, Inc.	5	9
Ceanic	6	15
Global Industries, Ltd.	1	1
Oceaneering International, Inc.	36	51
Racal NCS	5	9
Sonsub International, Inc.	11	23
Subsea International, Inc.	4	6
Total Systems Operating in the Gulf	70	116

*Information source – Contractor survey by Drew Michel
Updated 20 July 1998

Triton XLII
Work Class ROV

Arctic

Russia is finally going to open up, with major developments offshore about to be exploited. Some of these prospects will be in water depths of 1,312 ft (400 m) and in the icy Barents Sea and Kara Sea. The largest gas reserves in the world are said to be located in these areas.

Africa

West Africa is a major hot spot with the following activity and new leases available in water to 8,383 ft (2,555 m).

- Exxon is drilling off Nigeria in 4,836 ft (1,474 m) in the Gulf of Guinea and is exploring in depths to 6,601 ft (2,012 m) offshore of the Congo.
- Mobil is drilling in the Kwanza Basin off Angola in 2,493 ft (760 m) of water.
- Elf Aquatine SA is working in 4,478 ft (1,365 m) in the Angolan field Girassol and at 4,117 ft (1,255 m) in Dalia.
- Vanco Gabon Inc. and Reading & Bates Development Co. are planning ultra-deep exploration offshore of Gabon in 8,200 to 9,900 ft (2,500 to 3,018 m).

Other

Other areas where ROVs are required are off Newfoundland, Alaska, the Caspian Sea off Azerbaijan, Trinidad, the West Coast of California, off Australia in the Indian Ocean, the Bass Strait in the Tasman Sea and the Mediterranean Sea off Egypt.

- Woodside Offshore Petroleum is developing the deep water Laminaria field located in the Timor Sea in over 2,953 ft (900 m).
- Petergaz of Russia is performing a route survey for a Black Sea pipeline that will stretch between Russia and Turkey. The pipeline will be 30 percent deeper than any other existing line.
- Transocean is building the 850-ft (259-m) drillship *Discoverer Enterprise*, which will be capable of exploratory drilling in depth to 10,000 ft (3,048 m).
- Shell Offshore has contracted with Ray McDermott and Aker Marine for a spar style drilling rig capable of 10,000 ft (3,048 m) operations.
- Aker UK has completed study for development of Indonesia’s Makassar Strait in up to 4,921 ft (1,500 m).

CHAPTER 5. HOW SUCCESSFUL ARE THEY?

The success of modern ROVs can be addressed on several planes. The military has been using such systems for some time, especially for search, recovery and mine countermeasures. The academic community is increasing ROV and AUV applications, and their use for oceanographic research continues to grow. However, the largest use of ROVs is for offshore oil and gas exploration and production (E&P) support, essentially because that is where the money is. Accordingly, the discussions in this chapter will be based primarily around their successes in offshore applications.

DEEPWATER DRILLING SUPPORT

Today, the ROV is entering a period of great opportunity. With E&P depth increasing, and the upgrading and building of new rigs, the ROV becomes the "last resort" more regularly. To provide examples of ROV use and philosophy, material from a presentation made by Oceaneering–one of the world's leading ROV operators–will be used throughout this section. The projected deepwater drilling support in the future will require:

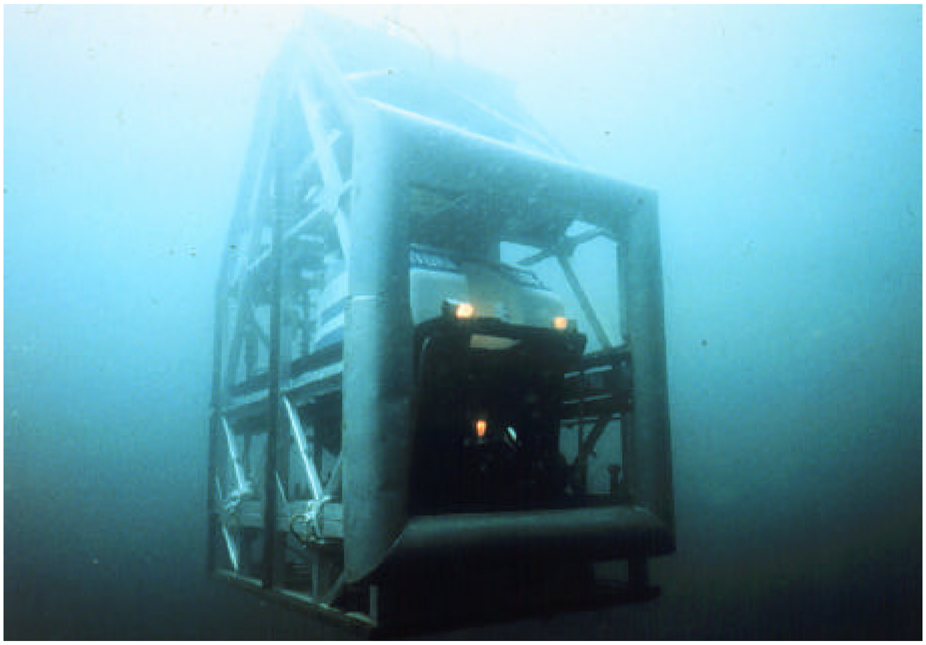
- Drilling support to > 9,843 ft (3000 m)
- Construction/Installation support to > 8,202 ft (2,500 m)
- Production support to > 8,202 ft (2,500 m)
- Enhanced tooling and operational performance
- Enhanced operating envelopes
- Added value

This section will address the area of deepwater drilling support by ROVs.

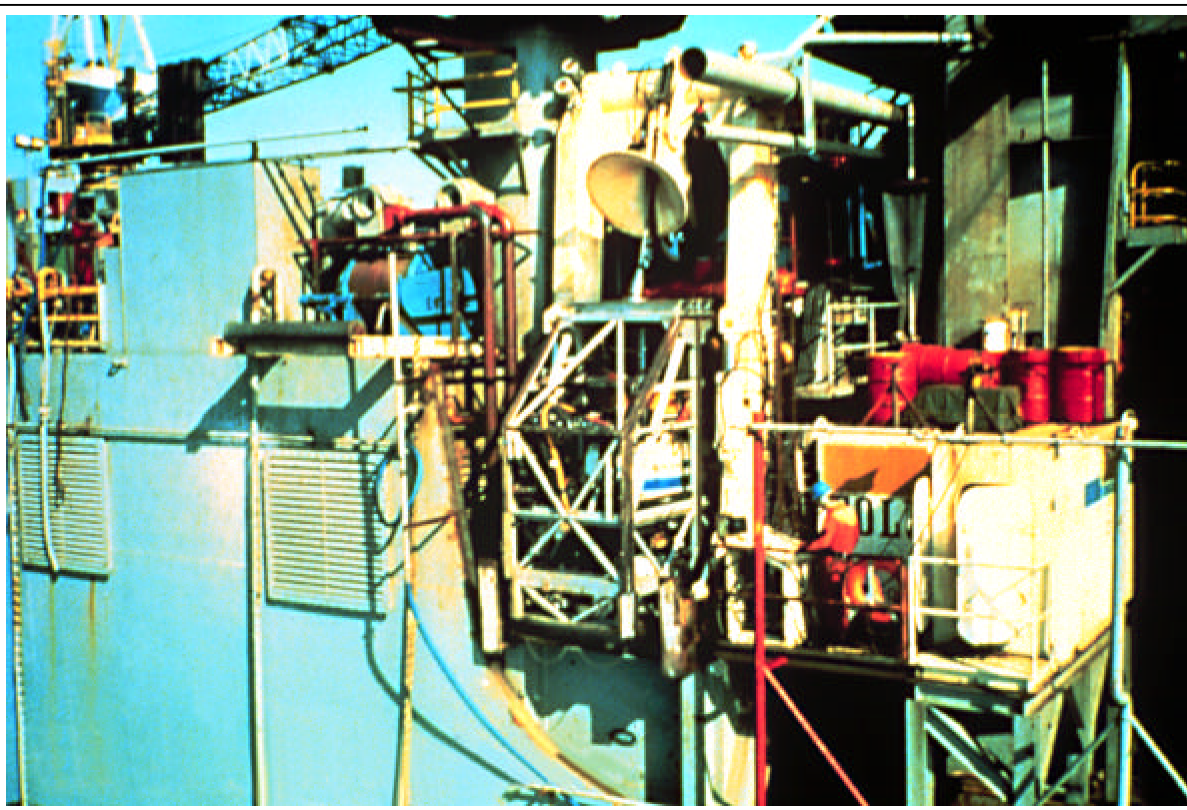
Introduction

The era of deepwater drilling support by ROV essentially began in 1983 with Shell's decision to utilize an ROV to support the *Discoverer Seven Seas'* deepwater program off the US East Coast. This program called for the support of drilling operations in the 4,921 to 7,546 ft (1500 to 2300 m) depth range, which represented more than a doubling of the drilling support water depths at that time. Prior to this program, *Discoverer Seven Seas* had used one of the *Pisces* class of manned submarines, but low efficiencies, weather sensitivities, and safety issues led Shell to take the then bold step of utilizing an ROV for this support.

The *Hydra 2500* (see figure next page), is a cage deployed ROV system built by International Submarine Engineering for Oceaneering to support Shell's program. *Hydra 2500*'s first working dive off the US East Coast was in 6,824 ft (2,080 m). Over the next 8 years, the *Hydra 2500* made over 2,000 dives off both the US East Coast and in the Gulf of Mexico with over 400 dives being deeper than 5,577 ft (1,700 m) and 800 dives deeper than 4,265 ft (1,300 m). The *Hydra 2500* proved that an ROV had a capability to routinely support drilling operations in deep water. Over an eight year period the ROV system remained onboard the drillship, in a location directly exposed to the elements.



Hydra 2500 **Drilling Support ROV**



The *Hydra 2500* onboard the *Discoverer Seven Seas*

Essentially, the *Hydra 2500* established the deepwater drilling support market for an ROV and was instrumental in proving that an ROV, even in 1983, was capable of providing useful, reliable, cost effective support.

The *Hydra 2500* was followed by *Hydra AT*, which supported the *semisubmersible Zane Barnes/Jack Bates* over a nine year period of 2,000+ dives in water depths of up to 1680 msw. The *Hydra 1095/Quantum 5* system has supported the *Discoverer 534* for over five years in water depths deeper than 9,448 ft (2,880 m) and held the oil and gas industry's deepwater drilling support record. For over 15 years *Hydra 2500*, *Hydra AT*, *and Hydra 1095* have firmly established the role of the ROV and its ability to support drilling operations in any depths where drilling can take place. With ROV dive records such as shown in the following table of 1997 statistics, where do we go from here?

HYDRA 2500

- *Discoverer Seven Seas*
- Dives: > 2,000 dives
- 800 dives > 4,593 ft (1,400 m)
- 400 dives > 5,905 ft (1,800 m)
- Deepest Dive > 8,071 ft (2,460 m)

HYDRA AT

- *Zane Barnes/Jack Bates*
- Dives: > 2,200
- Deepest Dive: 4,987 ft (1,520 m)

HYDRA 1095

- *Discoverer 534*
- Deepest Dive: 9,121 ft (2,780 m)

Deepwater Drilling Support - 1998 And Beyond

The industry is moving into a new era in deepwater drilling. Until quite recently there were only a handful of rigs, predominately drillships, which could drill in water depths greater than 4,921 ft (1,500 m). As a result, each project was of a one-off variety with focused planning, preparation and execution. The limited number of such projects allowed for the organization of highly experienced support teams, and ROV support services were no different.

However, the industry has now entered a period that not only includes a rapidly expanding deepwater drilling fleet but also a dramatic expansion of subsea projects in general. This dual expansion has significant implications in that the expansion of the deepwater drilling business alone would have stretched existing ROV resources. The expansion of deepwater drilling and the higher levels of performance, equipment, expertise, and experience required, in combination with the expansion of subsea projects, creates a significant challenge to the industry overall. The ROV industry is now faced with the most significant challenge in its history.

Deepwater ROV Capabilities

The capabilities required for efficient ROV support of deepwater drilling and production, defined as greater than 4,593 ft (1,400 m) deep, are centered around:

- ROV system and capabilities
- Installation and launch configurations
- Personnel
- Organization and backup

In 1992 Oceaneering recognized that there would be an upsurge in intermediate to deep water drilling–5,249 to 9,843 ft (1,600 to 3,000 m). In order to address the evolving opportunities, Oceaneering also conducted a detailed analysis of existing work class ROVs and their deepwater operational capabilities to determine suitability for these upcoming requirements. The result of this extensive analysis led to the following criteria as key to successful deepwater operations.

- Compact
- Powerful
- Cage Deployed
- Redundant Subsystems
  - Control
  - Fiber Optics
  - HPUs
- Reliable
  - Diagnostics
  - Troubleshooting
  - Worldwide update via Modem
- Maintainable

Based on the previous analysis of the overall capabilities of existing work class ROVs, Oceaneering decided to manufacture a new series of deepwater work ROVs, developed specifically for deepwater operations: the *Magnum*, *Millennium*, and *Phoenix* classes. With the upcoming operational depths expected, Oceaneering decided to develop all ROVs with customer requirements in mind, i.e. make them all deep. How these new systems met the design criteria for deepwater ROVs follows:

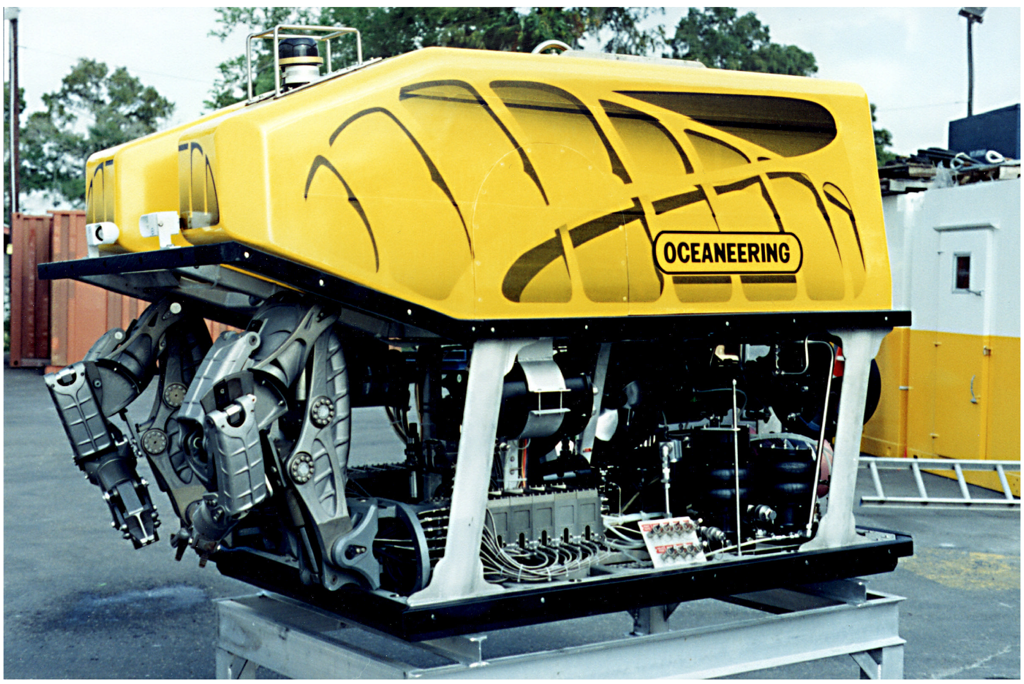
Compactness & Power

The performance and capabilities of these classes of deepwater ROVs are summarized:

	Magnum	***Millennium***	***Phoenix***
• Depth Rating (m)	2,500 (min)	3,100	2,600
• Horsepower	75 & 100	150	225
• Bollard Pull (kg)	400 & 550	900	1,000+
• Net Buoyancy (kg)	150	400	500+
• Deployment	Caged	Caged	Liveboat
• Tether Length (m)	183	183	N/A

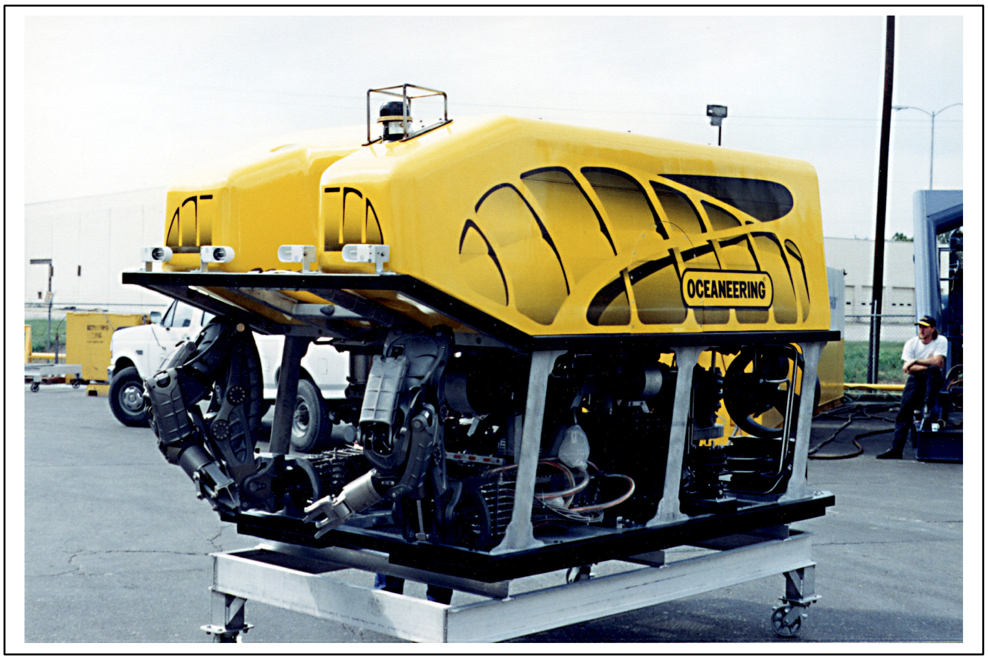
The *Magnum* is a compact, powerful, cage deployed work class ROV capable of carrying out the full range of drilling support tasks in water depths to 8,530 ft (2,600 m). In addition, it is capable of supporting construction, installation, and long term production operations.

***Magnum* Deepwater ROV**



In 1997 it became apparent that a number of the new generation deepwater drillships were being outfitted to support Extended Well Testing (EWT) and, in some cases, Early Production (EP). In addition operational procedures were being developed for dual drilling operations to reduce drilling times and take advantage of additional efficiencies made possible by parallel operations. The net result was that the ROV would be called upon to carry out a much wider range of work tasks and also perform multiple work tasks on single dives. In 8,202 ft (2,500 m) the round trip transit time will normally approach 3 hours, or more. In the event of deteriorated surface conditions these times will grow. Recovering an ROV to outfit it with a different set of tooling, hydraulic intervention capability, jumper connection capability, etc., will further add to this lost time.

In order to accommodate these heavier payloads, increased hydraulic capacities for tooling, and increased overall performance, Oceaneering developed the 150 hp *Millennium* class of cage deployed work class ROVs. The *Millennium* is somewhat larger than the *Magnum* and incorporates increased capabilities throughout. Oceaneering had already designed and built five 150 hp work class ROVs rated to 7,218 ft (2,200 m) or greater as well as sixteen 75 hp *Magnum*s and three 100 hp *Magnum*s all rated to 7,218 ft (2,200 m) or greater, and took advantage of this experience to design and outfit the *Millennium*.



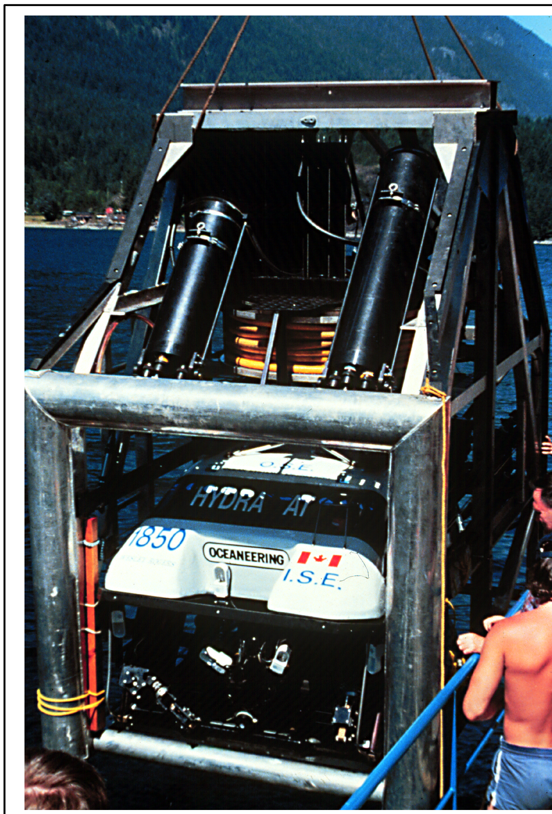
***Millennium* Deepwater ROV**

As shown in the following figure (see next page), the pedigree between the ROVs is obvious, however, as shown in the earlier table, the *Millennium* ROV is the larger and more powerful of the two. In addition to the ROV itself, it is essential to take into account the performance of the overall system. Other major issues are deployment methods and umbilical reliability.

Magnum* vs. *Millennium

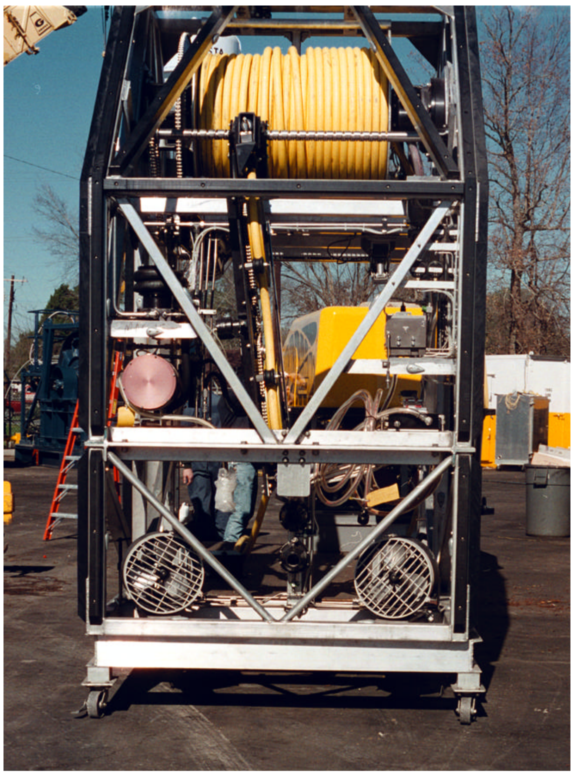
Cage Deployment

Oceaneering operates only cage deployed ROVs to support deepwater drilling operations (see figure to right). They also operate a large number of tophat based ROVs and are thus in a unique position to evaluate the relative merits of both approaches. The ability to tune cage weight to the drill vessel's motion characteristics and overall environmental conditions is a greatly undervalued capability and one not well understood by the industry in general. In addition, the cage configuration allows for more efficient tool deployment, heavy load placement, special BOP intervention with high volumes of fluids, etc. These capabilities can be mounted on the cage when appropriate, thereby allowing the ROV to operate freely without being encumbered by this hardware throughout a dive. In addition, mounting these capabilities on the cage allows multiple operations to be carried out in a single dive, thus eliminating the



need to return to the surface and install a different tool–a time consuming operation in deep water. The cage provides protection for the ROV during the most critical part of the operation. This protection also allows the system to be launched and recovered in higher sea states than a tophat system. A liveboat ROV operation is even more vulnerable. In addition, the weight of the cage can be adjusted to address vessel motions, which can have a significant impact on the reliability of deepwater umbilicals.

Developed along with the Magnum ROV by Oceaneering was the Vectored Orientation System (VOS) – a pair of high performance thrusters mounted on the cage and powered by up to a 75 hp HPU. The thrusters are tied into a gyro and joystick so the cage can be flown in conjunction with, or independent of, the ROV. The benefits provided by the VOS include:



- Orients cage in vicinity of rig members/hull
- Holds cage off/away from same
- Increases working footprint of ROV
- Allows cage to deliver attached equipment that ROV can interface with

A *Magnum* ROV with VOS (left)

Another Oceaneering concept is the "slotted cage." One of the purported weaknesses of a cage is that it limits the size/shape of the work package the ROV can carry. In this concept, the work package has an adapter that fits in the cage floor slot.

ROV Cage with Detachable Flooring

Umbilical

The impact of vessel motion, incipient snap loading, etc., on deepwater umbilical reliability is not well understood by many. The failure of a deepwater umbilical is the most disruptive situation that can occur in drilling support. It is easier, quicker, and less disruptive to replace a lost or damaged ROV than a failed or defective deepwater umbilical. Assuming a spare is available, replacing 8,202 ft (2,500 m) of umbilical under 11,025 lb (5,000 kg) of pre-tension is an exhausting, time consuming task. ROV specifications must address more than horsepower, lighting, manipulators, valving, etc. The umbilical is the single most important part of the system. Over a three-year contract, the ROV company that understands and addresses this single issue will provide a less expensive and more reliable service than an ROV offered at a much lower dayrate. With program costs exceeding $240,000/day, deepwater experience, reliability, backup systems, organizational experience–and understanding umbilical designs–are key issues.

Redundant Subsystems

Oceaneering's deepwater drilling support ROVs have always incorporated redundant HPUs, identical manipulators, cameras, and specific control subsystems as well as enhanced diagnostic and troubleshooting capabilities.

A representative example of redundant subsystems is redundant HPUs. The delays and costs associated with aborting a dive, should an HPU fail, is exacerbated by deepwater operations. In depths of 4,921 ft (1,500 m), an aborted dive can result in the loss of three hours or more when compared to more conventional depth drilling programs. This lost time is simply the time it takes to recover, to surface and redive to operating depth–independent of repairing the failure itself. The difficulties, risks and resulting lost time associated with recovering a "dead" ROV will be in addition to the lost transit times. Recovering a "dead" ROV in a tophat or liveboat configuration can/will be difficult in deepwater, more so with strong subsea currents or surface conditions. These conditions can result in entanglement of the ROV around the riser, damage to the ROV, or loss of the ROV itself. With total deepwater/remote area drilling program costs approaching $I0,000 per hour, the minimum cost of such a failure, considering only the lost transit time, can exceed $30,000 with a tophat or liveboat system. The actual lost time will be considerably more than this depending on the configuration of the system. A key advantage of a cage deployed ROV is that recovery of a "dead" ROV is only marginally more difficult than that of a "live" ROV. With the Vectored Orientation System (VOS) capability the recovery is fairly straightforward, as the cage can be oriented directly with the "dead" ROV. Tophats and liveboat ROVs become a liability at such times.

HPUs on ROVs experience failures, infrequently in most instances, but this fact has led to the use of dual HPUs on many of the newer systems. A working dive can be easily completed with a single HPU, so the failure of a single HPU is minimal, with no impact on the drilling program if a backup system is available. As noted previously, an ROV with only a single HPU is at considerable risk should an HPU failure occur. This dual HPU configuration has proven valuable over the years, as the failures, when they occur, do not have an impact on the drilling program.

Installation and Launch Configurations

The various drilling rig configurations–semisubmersible or drillship–lead to somewhat different installation and launch configurations. Until recently, the semisubmersible was the more prevalent drilling rig, except in deepwater, because of its stability. However, as the new era of deepwater drilling is entered, the drillship is taking a leading position. The *Discoverer Seven Seas* and *Discoverer 534* are representative of the existing fleet of drillships. This group is growing rapidly. However, it is the new class of super drillships, 984 ft (300 m) long and >75,000 ton displacement, that are opening up new capabilities in the 8,202 to 13,123 ft (2,500 to 4,000 m) water depths. They also provide the ability to combine drilling, extended well testing and early production in a single rig.

In order to provide the most effective capability to support these drillships, Oceaneering has developed a number of new, or improved, approaches to installation and launch. These, which are discussed in the following sections, can be summarized as:

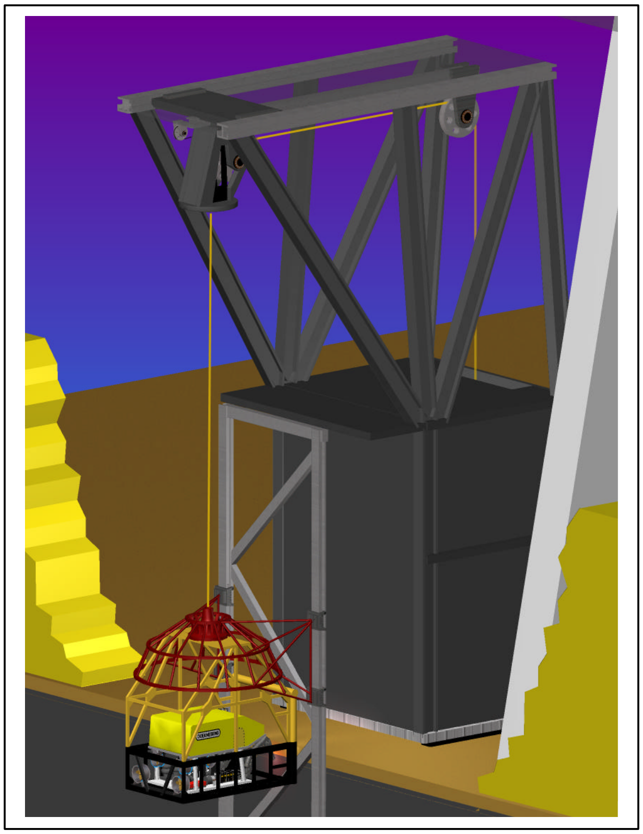
- Installation concepts
- Launch and recovery concepts
- High current operations

Installation Concepts

In spite of the increased size of the new super drillships, deck space, particularly in the mid ship area, remains a premium. For at least the past 15 years, space in this vicinity has always been fought for. The installation of the *Hydra 2500* onboard the *Discoverer Seven Seas* is referred to as the "Swiss Family Robinson" installation because the system operates over three main levels.

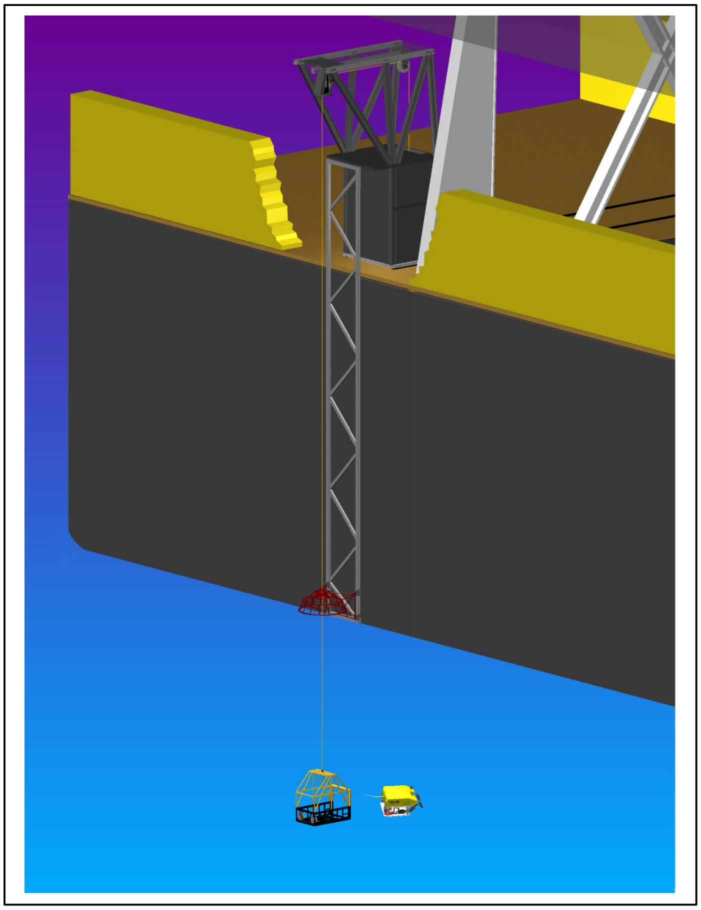
In order to optimize space onboard one of the new super drillships, Oceaneering and Transocean have developed an installation concept that utilizes the minimum space possible and permits the ROV system to be relocated to operate either over the side or through the moonpool. The ROV system is mounted vertically with a 24.6-ft x 22.3-ft (7.5-m x 6.8-m) footprint.

The winch, with an 11,483 ft (3,500-m) umbilical, is installed on the lowest level to minimize the overturning moments during launch and recovery. The winch is fully enclosed to protect it from green water that will be present in the midship area. The intermediate level houses the control and maintenance areas in separate built-in areas. Again, these are fully enclosed, air-conditioned and explosion proofed. The ROV system itself–cage, ROV, cursor and trolley–occupy the topmost level. The entire ROV installation is designed to be moved around the drillship on the BOP (blow out preventer) rails and can be relocated from an over-the-side launch to a through the moonpool launch in approximately eight hours.



ROV Deployment System

In order to eliminate effects of weather on launch and recovery, both locations are outfitted with guiderails that extend from the uppermost ROV location to the lower edge of the ship's hull. Both the over-the-side guiderails and the moonpool guiderails are designed for removal during transit or whenever the area needs to be free of any interference.



Over-the-Side ROV Deployment System

The over-the-side guiderails are designed to support launch and recovery during the entire weather-operational envelope of the drillship. Some of the new super rigs can work in up to hurricane conditions. The guiderails, which are removable for transit, are locked to the ship at the bottom of the hull, at the main deck level, and at the top level of the ROV installation. In addition, sets of compressible pads are mounted on the guiderail just below the water line. Thus, when the guiderails are stabbed into the bottom sockets and rotated back toward the ship's hull for attachment at the two upper locations, these pads are highly compressed and provide mid span stability to the guiderail truss structure. The moonpool guiderails are less robust and complex as they see considerably lower loads.

A cursor is then utilized with the guiderails to stabilize the cage/ROV during launch and recovery. The cursor is designed to provide the appropriate bend radius to the umbilical as it exits the cursor. As the drillship will operate in currents up to four knots, it is critical to protect the umbilical from contact with the ship's hull and also against excessively tight bend radii. As noted earlier, umbilical reliability will be a key factor in deepwater ROV operations and the configuration described above was developed with this in mind.

High Current Operations

In order to optimize operations in both deepwater and harsh environments, Oceaneering has developed the Vectored Orientation System (VOS). VOS, shown earlier in this section, consists of a pair of high power thrusters mounted on the cage. These thrusters are powered by up to a 75 hp HPU. In addition, the thrusters are integrated into a gyrocompass installed on the cage. The overall system is controlled by a separate joystick in the control room that allows the cage to be flown independent of, or in conjunction with, the ROV itself. In addition, auto heading, etc., is a standard part of the VOS.

At the surface, VOS is utilized to orient and locate the cage/ROV in the most efficient configuration for launch and recovery. It is used to hold the cage/ROV away from the rig structure, etc., particularly in the case of high currents. Overall a *Millennium* system with the VOS generates well in excess of 2,000 lb (907 kg) of thrust. In deepwater, the VOS is used to maneuver the cage to the most desirable location to support operations. It is used to translate the cage in the case of subsurface currents and to hold the cage in position once the ROV departs the cage. As a result, the ROV's operational envelope is greatly increased. Also, it is often desirable to leave the ROV near bottom for extended periods of time in deepwater operations, >4,921 ft (1,500 m), rather than recover it and relaunch it, particularly when surface conditions have deteriorated. The VOS allows the ROV to remain powered-down in the cage with only its lights and camera on. The VOS is used to hold the cage in a position such that subsea operations can be continually monitored if required. This configuration allows the ROV to remain on location for extended periods and yet not be operating. As the ROV is the most complex piece of the system, this combination improves reliability through continuous support of deepwater operations.

Operational Support and Backup

In all the areas of the world where deepwater, remote, or high cost operations are conducted, an extensive support and backup capability is necessary. This consists of the following major components:

- Expanded onboard inventory
- Regional inventory
- Worldwide inventory
- Backup winch with umbilical
- Backup ROV

The expanded onboard inventory is sized to allow extended operations without resupply. This is particularly important in areas such as West Africa and Asia where distances and transportation result in long turnaround times for parts and personnel.

Regional inventories must be sized to support ROV operations in applicable areas. This inventory includes everything in an onboard inventory plus an additional $300,000 worth of components.

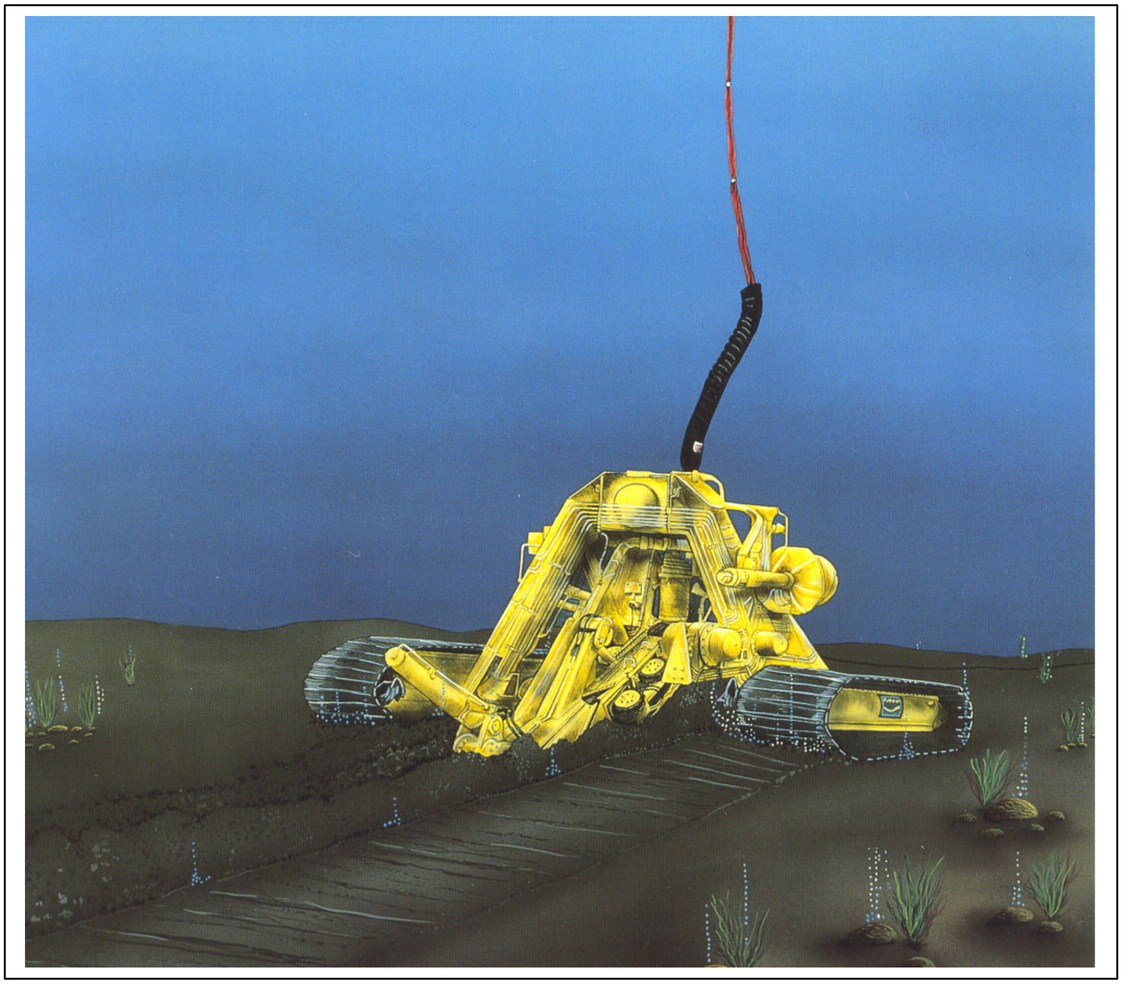
The worldwide inventory, based in a single location, typically consists of over $1.5 million worth of components. Every ROV component is held in this inventory. In addition, all of these inventories–from onboard to worldwide–should be linked by a standardized inventory database that utilizes a bar code system to track and maintain quantities, locations, reorders, etc.

In addition to this extensive inventory system, a backup winch with an umbilical capable of supporting the deepest operations in the area, as well as a backup ROV, should be maintained at major operating bases. No piece of equipment can be perfectly protected from damage or failure, but a system can be put in place that absolutely minimizes the impact and protects against extended downtime in the event of a catastrophic event.

CABLE BURIAL OPERATIONS

Introduction

The area of cable burial operations is a complex and fascinating realm. And, as the capability of trans-oceanic cable systems increase with the installation of fiber optic cable networks, so does the cost of downtime to the owners. Accordingly, the role played by the many types of ROVs (as shown by the examples in Chapter 2, Telecommunications Support), from burial plows to sophisticated repair systems, is becoming increasingly important. An excellent perspective on the cable burial industry, from history, to installation and burial techniques, and ultimately repair, was published by Howie Doyle in the Summer 1997 issue of *UnderWater* magazine. That article, combined with material from other sources, makes up the following section, which provides an excellent overview of the technology required to successfully install and maintain undersea cable systems.



TECNOMARE's TM 402-C Cable Trenching Vehicle

Background

Back in 1858 the first transatlantic submarine cable was installed for telegraph use. Nathaniel Hawthorne, inspired by the development of the telegraph, said “is it a fact–or have I dreamt it–that, by means of electricity, the world of matter has become a great nerve, vibrating thousands of miles in a breathless point of time?”

The great nerve is again being transformed by means of light. In 1988, AT&T Communications laid Transatlantic Cable #8 (TAT-8), the first Transatlantic fiber optic cable ever, linking the New World to the Old. Probably, not even they could have imagined the importance of this new medium, this new way of making the world a smaller place.

Traditionally, in order to access information, we have moved to it. The information consisted of atoms (books, newspapers). Now the information, in the form of photons and electrons, moves to us–digitally. Optical fiber, which is made from the most common element on earth (silica), is the cheapest, fastest way to connect divergent points with large amounts of data.

In 1996, Submarine Systems International scientists transmitted one million bits of data in a single second through a pair of optical fibers. William B. Carter, president and CEO of SSI, characterized this phenomenon. “A single pair of fibers will someday have the capacity to carry over 1,000 billion bits of information per second,” Carter said. That’s equivalent to half a million simultaneous two-way high definition television channels across fibers that are the width of a human hair,” he added.

Fiber optic cable, both underwater and land-based, will become the “wired” infrastructure of the 21st century. Fiber optic trunk communications channels will link more than 280 countries with voice, fax, and modemed communications. The underwater industry will enjoy a surge in revenues generated through installing, maintaining, and repairing this fiber optic infrastructure.

When Demand Exceeds Bandwidth

As a digital medium, twisted copper wire pairs are too slow and the material too expensive (although there is still a lot of it in place that we will be forced to use for a while). A 4.5 lb (2 kg) spool of hair-thin optical fiber can transmit the same amount of data as 200 reels of copper wire weighing almost a ton. Satellite communications and microwave radio have limited available bandwidth, adversely large round trip delay, and, unlike fiber optic, severe limitations on bit rates. However, they will be well utilized for specialized remote communication needs outside of our requirement for trunk communication channels.

None of this would be too significant if it were just for the sake of improved telephone communications. After all, how many people can talk on the phone at one time to their European relatives? Even the Internet couldn't require too many additional phone lines, you think, as you browse the World Wide Web with your 28.8 kbps modem.

There is a trend on the Internet, however, that is a bellwether for the digital lifestyle we will all lead as we enter the 21st century. Most of us have seen the cute little icons (called animated GIFS) that spice up many web pages. They consist of, for instance, a letter that folds itself up and inserts itself into an envelope, signifying email. Or perhaps the telephone graphic that vibrates as if it were ringing off the hook. Some Web pages are even enhanced through the use of audio clips.

Project this into the future, and you will have real-time, full motion, high quality audio-video on the Internet, which will require an exponential increase in the amount of data that must be transmitted–quickly–to our home computer (or Internet appliance). Imagine, then, that you receive all of your video entertainment over the phone lines. Videotapes will become a thing of the past, as will video stores. You will order movies through your Internet appliance, which will sit in your living room where your television used to be. You will download the movie when you wish, and you will watch it when you wish. Or instead, you may prefer to participate in virtual reality action battle games with other players, in real time. Your "character" will display your facial expressions, will verbalize your exclamations, and will represent you in great detail. With these video capabilities, there will be many other things you may wish to do.

You may conduct real time video conferences, where all participants will be sitting at their desktop computers, which will have tiny, high-quality digital cameras mounted atop the monitors. During these conferences, you will view full color graphic presentations of data and video. It will be like sitting in the same conference room, without the travel expense, noisy hotel and lumpy bed. So the driving trend in the Internet bandwidth dilemma is incorporation of high-resolution graphics and video. But there are other macro-trends that create data packets that require a lot of bandwidth as well. International corporate intranets, which utilize the same data channels as the Internet, keep geographically dispersed offices connected. LANs and WANs use phone lines for connectivity. Home connection rates to the Internet are still increasing rapidly; the paradigm for data transfer rates keeps moving upward.

Underwater fiber optic cable carries all of these types of data to the various landmasses of the world. Additionally, in the process of wiring the various residential and business areas within the continents, it is frequently necessary to traverse bodies of water. In the past it was common to skirt the perimeter of a lake, or to utilize an above-water crossing of a lake or river by installing utility poles. However, underwater cable lay methods have evolved to the point that they can compete on a cost basis with land-based cable burials.

The electronic global village is steadily moving toward becoming a reality. A high capacity infrastructure connecting the developed nations of the world–the so-called Global Information Infrastructure (GII)–will be in place by the year 2015, according to industry experts. The economic fates of nations will hinge on their ability to access the GII and compete in the global economy. Neal Stephenson states in *Wired* magazine: "The financial districts of New York, London, and Tokyo, linked by thousands of wires, are much closer to each other than, say, the Bronx is to Manhattan."

A major cornerstone in the Global Information Infrastructure expansion is the FLAG (Fiber-optic Link Around the Globe) Cable System. FLAG was successfully completed on June 9, 1997, and is currently the world's longest fiber optic cable system, with over 16,781 miles (27,000 km) of cable, 335 repeaters, and 6 branching units. This cable system provides a communications link to the United Kingdom, Spain, Italy, Egypt, the United Arab Emirates, India, Malaysia, Thailand, Hong Kong, China, Korea, and Japan. A consortium of investors privately finances FLAG, which went on line in September 1997. Submarine Systems International (formerly AT&T Submarine Systems) of the United States was the lead contractor for this system, subcontracting to both KDD of Japan, and Cable and Wireless Marine of the United Kingdom.

The Africa ONE project is a fully integrated multi-technology network, which links the countries of Africa to each other and the rest of the world by utilizing 24,239 miles (39,000 km) of undersea fiber optic cable. Africa ONE forms a ring around the continent of Africa that will connect about 29 coastal country landing points. Countries without landing points, including interior countries, will use terrestrial fiber, microwave, or satellite facilities to connect to Africa ONE's landing points.

Africa ONE will link African Carriers directly to Italy, Greece, Portugal, Saudi Arabia and Spain. These carriers will be connected to the rest of the world through existing and planned submarine cables. Submarine Systems International and Alcatel Submarine Networks are coordinating the project. Installation of the Africa ONE cable system is scheduled for the second half of 1998, with a ready-for-service date in the first quarter of 2000.

The Atlantic Crossing cable system (AC-1) is a high-capacity, undersea fiber optic ring network with direct connectivity between the United States, the United Kingdom and Germany. This four fiber self-healing Synchronous Digital Hierarchy (SDH) network spans over 8,701 miles (14,000 km) and will initially provide 10 Gbps per fiber pair of transport capacity. Submarine Systems International developed this project for the Bermuda-based Global Telesystems Ltd.

AC-1 will be implemented in two phases: Phase I will provide connectivity between the United States and the United Kingdom. Phase 2 will provide direct link connectivity between the United States, Germany, and the United Kingdom, thus closing the ring. Both phases are scheduled for completion in 1998.

The behemoth 23,617 mile (38,000 km) SEA-ME-WE 3-fiber optic system will connect 33 countries in South East Asia, the Mediterranean, and Western and Central Europe. To be constructed by a number of suppliers including Alcatel, KDD, Fujitsu, SSI and Pirelli, the network is scheduled for service in December 1998. Total cost to construct the system is expected to reach $1.3 billion, and it will have an initial capacity of 20 Gbps (equal to approximately 240,000 telephone circuits). Two other transatlantic systems–Gemini–will soon be installed by Cable & Wireless Marine, with cable by Alcatel, to link the United Kingdom to the northeastern United States.

Worldwide, there are now well over 300 submarine cable systems in operation. Because of growing demand, and shifting paradigms, outdated systems are being retired constantly, and new ones laid to replace the old. Currently only about 60 nations are tied into the global fiber optic network. By the end of the 1990's, more than 100 countries will be connected, which means there are many fortunes to be made. Hundreds of thousands of miles of undersea fiber optic cable will be laid as we weave the world's landmasses together in the next decade. And while the transoceanic contracts will land in the hands of the major players, the ripple effect to ROV and cable plow manufacturers, diving and ROV contractors, sonar system manufacturers, data acquisition system designers and others will be substantial.

A handful of contractors provide shore end landings and cable burial out to depths where transoceanic vessels operate. Most of these contractors also perform installations of short-haul, shallow water systems. Submarine cable maintenance and repair is also big business–getting bigger–for underwater contractors, and is suited to the smaller, "call-out" oriented contractors using non-specialized vessels or vessels of opportunity. Thus, the demand for bandwidth translates into a demand for the underwater technologies that, in many cases, trace their pedigree to the offshore oilfield.

Cable Ships - Purpose Built

The large telecommunications infrastructure companies of the world own purpose-built and multi-service vessels outfitted for the laying and repair of submarine fiber optic cable. Cable & Wireless Marine and Submarine Systems International are the biggest players, maintaining twelve and seven vessels respectively. France Telecom, KDD Submarine Cable Systems, Temasa, Asean Cableship Pte. Ltd., Teleglobe Marine, and Tele Danmark also operate cable ships. Most of the entities are huge conglomerates that have ownership in the cable systems they install, although, some even manufacture the cable system components.

Each of these multi-million dollar cable ships has unique capabilities, but most share a similar array of cable handling equipment for paying out and retrieving cable, and handling splice boxes and repeaters. The cable highway covers a path that runs almost the entire length of the ship. The description of equipment that follows represents a composite of typical cable ships outfitted for transoceanic cable laying.

Caldwell Diving Company's *Marion-C II* Cable Laying Ship

Above is Caldwell Diving Company's *Marion-C II* cable laying ship, a 195-ft (59.4-m), 4 point vessel that is outfitted with specialized cable laying and plowing equipment. Compared to some of the cable laying ships, the *Marion-C II* would be considered small. Crew size on some cable laying ships will often exceed 100. The crew will work in three shifts to allow 24-hour operation. At the bow of many ships, which may reach 500 ft (152 m) long and 75 ft (23 m) wide, large rollers called sheaves pay out (or recover) cable to the water. Alternately, the cable will run smoothly over the stern through a cable trough and chute. A linear cable engine, which is operated from a cable control room near the stem, controls the paying out or recovery of tensioned cables. The cable is guided through paired rubber tires that gently grip and pay the cable out with proper tensioning. The sophisticated controls allow cable lay speeds of up to 8 knots (14.8 km/hr), although usually closer to 5-6 knots (9.3-11 km/hr), without a loss of precision.

A major trend in cable laying methods in recent years has arisen from not only the use of optical fibers, but in the unrepeatered distances between optical amplifiers, or repeaters. The resulting proliferation of single systems utilizing small diameter cables has brought with it a marked change in the type of vessel employed and the cable machinery being used. Smaller diameter (or "skinny") cables cannot be handled easily by wheel-type linear cable engines (LCEs). Caley Ocean Systems has developed the Multi Track LCE, which uses a series of caterpillar tracks. This engine maintains the high-speed body-passing capability of the wheel type LCE, but is able to provide the required back-tension with a far shorter engine. This has opened up the possibility of containerizing the cable machinery, and using it in modular fashion on vessels of opportunity.

In cable ship operations, dynamometers, or load cells, continually monitor the cable tension and interact with the cable engine and thruster controls to avoid damaging the cable. In the midship area, giant cable tanks boast a storage capacity of up to 2,500 miles (4,000 km) or more. In the test room technicians will continually monitor the transmission performance of the fiber optic cable and repeaters as they are being laid. Bow and stem thrusters coordinate with the main propulsion unit through a dynamic positioning system to provide exact compliance with the specified cable route while compensating for currents or wind. One or two main propellers, with diameters as large as 13 ft (4 m), deliver 10,000 shaft horsepower for primary propulsion.

Cable ships will usually have a centralized control center that monitors, via integrated computer displays, engineering and cable-handling functions, in concert with navigation of the vessel. Differential global positioning systems (DGPS) allow operators to pinpoint the position of the vessel within 10 ft (3 m) in most areas of the globe. Software packages integrate data feeds from different sensors to provide installation control and data logging. The computer system feeds data to dynamic positioning systems so the vessel can move along a design route at a constant speed. Additionally, the system feeds data to cable machinery to ensure the cable engine pays out cable at a constant speed that is related to ship speed via slack. The software often communicates with cable engines and drums to monitor and record cable count, speed, and tension.

Several telecommunications giants use WinFrog, a Windows-based software system, in their control suite. Developed by Racal Pelagos, WinFrog is used in concert with its Ribbit post-processing and charting software to provide cable documentation, showing the as-laid location of the installed cable as well as other parameters (e.g. water depth, burial depth, cable tension, and slack). WinFrog is under development to include integrated cable management and slack control. It currently communicates with ROVs, plows, and tracked vehicles to integrate such data as vehicle speed, tow tension, submerged depth, trench depth, cable burial depth, pitch, roll, and cable tension.

These complementary systems permit the accurate installation of cable systems and provide for the rapid onboard production of as-laid charts. The Integrated Control System (ICS) developed by Makai Ocean Engineering is a real-time cable deployment control system. ICS generates real-time computer models of the suspended cable shape, and interacts with navigation and cable handling systems to lay or retrieve the cable along the desired path with the proper slack (or tension). ICS as a system focuses more on the condition of the cable as it touches down on the seafloor, than on primarily monitoring what is happening to the cable as it leaves the ship.

"The software development of the complex 3D real-time modeling would not have been possible without the recent development of fast computers, accurate seafloor surveys, good ship positioning in the open ocean and the Acoustic Doppler Current Profiler (ADCP)," stated Makai in a paper presented at the recent Sub0ptic '97 conference.

Threats to Cable in the Sea

"It sometimes seems as though every force of nature, every flaw in the human character, and every biological organism on the planet is engaged in a competition to see which can sever the most cables," according to *Wired* magazine's Neal Stephenson. Statistically, over 70 percent of the problems experienced with submarine cables occur in shallow water, due to the intervention of an outside party.

Fiber optic cables are installed in and on seabeds of all different conditions, ranging from "sugar sand" and silty substrates too soft to support burial equipment, all the way through hard rock and sandstone formations. Although the specified cable route will usually try to avoid difficult cable laying conditions, sometimes they are unavoidable. Add slopes, currents, and obstacle avoidance, and the on-site task of burying or protecting underwater cable becomes formidable. These considerations are especially prevalent in coastal locales. The current at the mouth of a river could present scour problems, or even cause chafing of the cable against a rocky bottom. A thorough cable route survey has been shown, through experience, to be imperative in planning a cost-effective system and in specifying protection techniques.

Anchors can also damage cable by snagging it and then pulling it toward the surface, or–if the vessel is large and the cable is not–by merely tugging on it as the vessel drifts. Because optical fiber is such an efficient communications medium, most fiber optic cable is not as large in diameter as power cable. Fiber optic or power cable need not be completely severed in order to quit functioning. Kinking the cable beyond its minimum bending radius can damage inside components. A sharp impact can create a leak in the cable jacket. Seawater entering through insulation faults can short out the power path that supplies the subsea repeater. Also, the interaction of seawater with electricity and dissimilar metals can produce hydrogen gas, which will chemically attack the optical fibers.

Deepwater threats to cable also exist, requiring protection in the lay process into quite deep waters with terrain that can be characterized by peaks, valleys, channels, rock bottoms, and the presence of current. Though many of them are now dynamically positioned, offshore vessels still drop anchors into deep waters (albeit with more difficulty than vessels in coastal waters).

But the number one nemesis of submarine cable is the commercial fishery industry. The mutual dislike of cablemen and fishermen began in 1870, when a French fisherman hauled up a newly laid cable spanning the channel between England and France. Only hours after Napoleon III sent the first message to Queen Victoria, the Frenchman severed the cable and removed a section to take home. He reportedly thought it was either a newly discovered type of gold-bearing seaweed, or the tail of a giant sea monster.

To combat the threat from commercial fishermen, AT&T and other large submarine cable owners conduct extensive cable protection programs. These programs promote a "sharing of the seabed" concept by working with the fishing community throughout the entire life of the system. System routing, cable armoring and burial, along with proactive public awareness are key components of these programs. AT&T also sends trained personnel to commercial fishing ports near submarine cable landings to distribute system charts and information that outline the locations of the cables and the laws that protect them. AT&T has seen a significant improvement as a result of this program, and intends to expand the program to react to any other potential threats to undersea cable systems before they lead to cable down-time. According to a spokesperson for AT&T, "AT&T is continuing to work with the commercial fishing industry to better understand their needs and concerns in fulfilling their livelihood, as well as enabling them to work with us to prevent any further cable outages due to trawling or the anchoring of fishing vessels."

Recently, commercial companies that own or operate submarine cables have created the International Cable Protection Committee (ICPC). The objective of this international forum is to distribute technical information regarding their submarine cable systems. Using the communication network they are trying to protect, they have developed a world wide web page that is available to those in need of the information. The web site can be found at <http://elaine.teleport.com/~ptc/iscw/iscw.shtml>

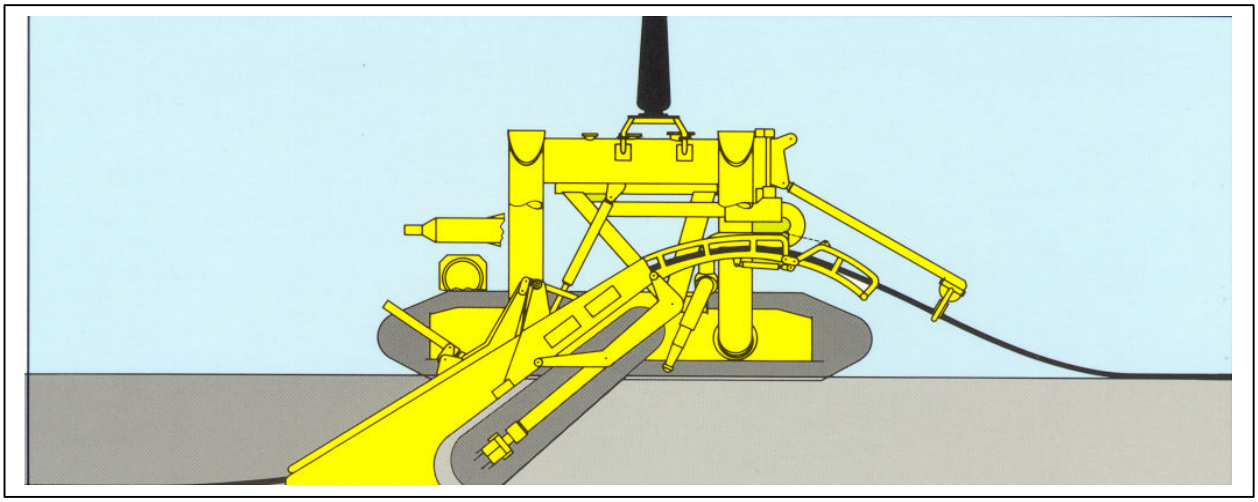
Options for Protecting the Cable

Because communications cables create revenue by selling capacity (circuits or bandwidth), every minute of downtime can result in an opportunity cost of thousands of dollars for the cable operator. As the capacity of fiber optic cable increases, so does the economic impact of a breach in service. Therefore, the need for preventive shielding is high. In most areas of the world, cable is plowed into the sea floor when in water depths of less than 4,920 ft (1,500 m), half-again the previous standard depth requirement for burial. Optionally, an armor or shield can be assembled around the cable either during or after it is laid. Installation represents about 15 percent of the total cost of a large-scale fiber optic submarine cable system. For repeaterless systems, installation can represent up to 33 percent of the cost.

For placement of the cable under the seabed, the tools currently utilized are cable plows (such as those shown in the figures on the following page), mechanical cutters, and water jets. Directional drilling is also sometimes used. Each of these systems is available from a number of manufacturers, and some cable laying contractors even manufacture their own systems to meet project requirements.

Telecommunications cables are available with various degrees of protection. Double armor for the near shore areas, single armor on the continental shelf, Fish Bite Protected (FBP) beyond the shelf to about 8,202 ft (2,500 m), and no armor at all beyond that depth, because of a lack of human activity and other threats.

Tecnomare's *TM 402-C* Cable Trenching Vehicle (left) and Concept of Operation (below)



In some regions additional cable protection is required. Traditional cable shielding consists of two half-shell segments of cast iron ducting, which are bolted on after the cable is in place, protecting the cable from impact and environmental damage. In some operations, articulated armor can be installed topside during the lay. But there is the problem of outboard weight when using iron in deeper waters. Also, in cases where corrosion of the iron due to water oxygenation is a problem, other materials must be considered.

Environmental impact must also be reckoned with. "We then have to consider environmental concerns in areas where there is a lot of coral on the sea floor. Rusty iron pipe is now considered offensive," according to Chris Cooper, of CWA Products Ltd. (UK). CWA manufactures polyurethane cable protection, which can be made to suit any size cable and can, if required, match the weight of the iron pipe.

CRP Marine has also developed polyurethane and polyethylene cable protection solutions, drawing on its expertise in the subsea petroleum industry. "Our Uraduct product has been used extensively for protecting cables and flowlines in the submarine oil industry for interface protection should a new telecoms cable cross one of their pipelines or cables," said Roy May of CRP, who added that the oil industry never uses cast iron ducting. CRP's Uraduct and Polyspace cable protection components have been used on the FLAG, SEA-ME-WE, Jasuraus, and numerous other systems.

Overall, marine cables can be divided into two categories: static and dynamic. Dynamic cables are used mostly for towing, control, umbilicals, and other functions where the cable will be in motion. Telecommunications and power cables, on the other hand, are considered static–except when they are being laid. Because the cable laying process requires motion and bending of the cable, bend limiters and stiffeners may be added during the lay process.

PMI Industries, Inc. of Cleveland, OH designs and builds bending strain devices for a variety of cables. Helical wrap-on rods are supplied by PMI for all sizes of bottom-laid trans-oceanic cables. This product provides a stiffening effect, preventing the cable from becoming kinked, and also protects the cable after it is laid. PMI also manufactures the Everflex line of bending strain relief devices for sea plows and many of the larger ROVs. PMI is represented by the MacArtney Group in many parts of the world.

Cable Burial: Methods and Equipment

Depending on the water depth, seabed condition, and the conditions dictating the burial depth requirement, there is a range of systems and burial modes that can be utilized. Burial is accomplished using a plow (figure on right), water jetting system, or a mechanical trencher. While various contractors and manufacturers will each have their own unique perspective on the relative strengths and weaknesses of each piece of equipment, certain general statements can be made about their respective characteristics.

PLOUGH PL2 **during launch**

The Cable Plow

The plow is a simple and reliable cable burial machine that was pioneered by Bell Labs over 30 years ago. It is a passive system, and as such it relies on the bollard pull provided by the vessel for forward motion. Most plow systems are not optimal for post lay burial situations. The plow has a wide range of effective seabed conditions in which it may operate, and is usually the fastest method available for soft bottom conditions. Cable plows will sometimes incorporate water injection features to assist in overcoming resistance in deep burial (not to be confused with deepwater) operations.

Speaking of deepwater, it is difficult to control a plow in very deep waters. In some deepwater operations there might be a 2.2-mile (3.5-km) span between the cable ship and the cable plow. Tracked vehicle cable burial and free swimming ROVs are commonly utilized where depth is a problem, although specifying a general depth at which plows are not effective is not possible, because a host of other criteria must be considered.

Water Jets

For many cable jobs, water jetting systems are utilized for burial. High pressure water fluidizes soil, creating the trench. The cable is usually pushed to the bottom of the resulting trench by a depressor, however, in firm seabeds and clay conditions the water jet may not be effective.

Mechanical Cutting Tools

Mechanical cutters are the monster machines of the cable burial industry. A rock wheel or chain cutter can be hydraulically driven by up to 1,000 hp of raw electrical energy provided through the umbilical. These cutters are used only where more moderate means will not provide effective burial. They are slow moving, high maintenance machines with greater support requirements than other cable trenching methods.

The Right Tool for the Job

Plows, jets and cutters all come in a variety of configurations, from many manufacturers. For every generalization that can be made about their application, there are many more specific points and exceptions to cloud the decision-making process. Fortunately, the bottom line is that the equipment works.

Seabed tractors or tracked vehicles are suited as a platform for both jetting and mechanical cutters. Their stout, stable footprint can accommodate powerful load-bearing manipulators when necessary. Although they can be quite heavy and must roll along on seabed, special wide track designs allow operation of some systems on all but the softest sea floors, or those with extreme bathymetry. Two of AT&T’s cable burial plows are shown in the following figures. A table highlighting some of AT&T’s past burial operations is also provided.

AT&T's *SEAPLOW VI*

AT&T's *SEAPLOW VII*

AT&T-SSI SEA PLOW BURIAL OPERATIONS

DATE	PROJECT	LOCATION	SEA PLOW	KM	RPTRS
July 1967	TAT-4/TAT-3	New Jersey	I	158	3
April 1968	St. Thomas 2	Florida	II	69	1
July 1969	TAT-5	Rhode Island	III	159	8
Aug. 1969	TAT-5	Spain	III	54	2
Aug. 1969	MAT-1	Spain	III	20	1
Sept. 1969	MAT-1	Italy	III	28	1
July 1970	TAT-4	France	III	178	4
Aug. 1970	TAT-3	England	III	139	3
June 1973	CANTAT-2	Nova Scotia	III	167	15
July 1973	CANTAT-2	England	III	148	13
Aug. 1975	TAT-6	Rhode Island	IV	176	19
Oct. 1975	TAT-6	France	IV	176	19
Feb. 1976	MAR-PAL	Italy	IV	31	3
Dec. 1981	ATLANTIS	Senegal	IV	37	0
April 1982	ATLANTIS	Portugal	IV	37	0
July 1982	TAT-7	New Jersey	V	157	17
Sept. 1982	TAT-7	England	V	276	29
April 1983	Denmark	North Sea	V	230	38
Sept. 1983	MERIDIAN	Spain/Belgium	IV&V	900	91
May 1984	TAT-5 Repair	Rhode Island	III	159	8
July 1985	SIN-HON-TAI	Hong Kong	V	204	12
Sept. 1987	TAT-8	New Jersey	V	113	3
June 1988	TAIPN	Taiwan	V	85	0
Nov. 1989	PENCAN-4	Spain	V	133	2
Jan. 1990	Korea Offshore	Korea	VI	139	2
May 1991	TAT-9	New Jersey	V	147	2
June 1991	TAT-9	Canada	V	155	3
Dec. 1991	TAT-10	Rhode Island	VI	177	1
Jan. 1992	TPC-4	California	VI	48	0
Feb. 1992	HAW-5	California	VI	67	1
June 1992	TAT-10	North Sea	VI	624	10
July 1992	TPC-4	Vancouver	VII	68	0
(+) Oct. 1992	DEN-RUS	Baltic Sea	VI	1,200	11
Various	x	x	x	1,258	x
		+ TOTALS		7,717	322

(+) Totals include Denmark-Russia burial operation now underway.

Free swimming ROVs are typically considered more of a cable survey, maintenance, and repair type of vehicle, than one used in long-haul burial. However, ROVs are used successfully in post lay burial jobs, and because they are free swimming, are especially effective for those in which the seabed is extremely soft, or on a grade too steep for a plow or tracked vehicle to operate.

Caldwell's Diving Company was an early innovator in the cable plowing industry. At this contractor's fabrication yard in Toms River, NJ, they have manufactured several plowing systems to accommodate a wide variety of seabed conditions. Their largest plow has an injection blade 105 ft (32 m) long, which weighs 5 tons (5,080 kg), and will bury cable in 400-ft (122-m) waters up to 40 ft (12 m) below the surface. This plow blade has individually controlled water injectors along the last 50 ft (15.2 m) of its cutting surface that deliver at pressures between 125-400 psi, depending on the resistance of the bottom material. The cable runs tension-free through a Teflon-lined cable path inside the blade, where it is then safely deposited in the bottom of the trench.

James Caldwell, whose company plowed the U.S. landing segment for each AT&T transatlantic TAT fiber optic cable (beginning with TAT-8 in 1988, through the recent TAT-13), has seen the industry mature. Indeed, he has been an integral part of it. Yet his is still a call for simplicity, as demonstrated by his almost exclusive reliance on cable plows to effect cable burial projects. The plows are computerized, in that they record cable tension, burial depth, pitch and roll, and other data during the operation. "Most of the challenges presented during a cable lay, which are dictated by bottom conditions, water depth, and burial depth requirements, can be overcome through proper engineering." In other words, horse sense first, high-priced systems and solutions later. Caldwell Diving Company's reputation in the industry is that of having the ability to bury cable deeper with smaller vessel size and support requirements, which translates into lower cost.

General Offshore is a shallow water contractor whose excellent reputation in the cable burial industry has been gained through reliance on a wide range of cable burial systems, weighted heavily toward tracked vehicles and remote technologies. Perry Tritech built the *Gator* tracked trencher system in 1994 for General Offshore, and since that time it has buried over 74.6 miles (120 km) of cable in a variety of seabeds.

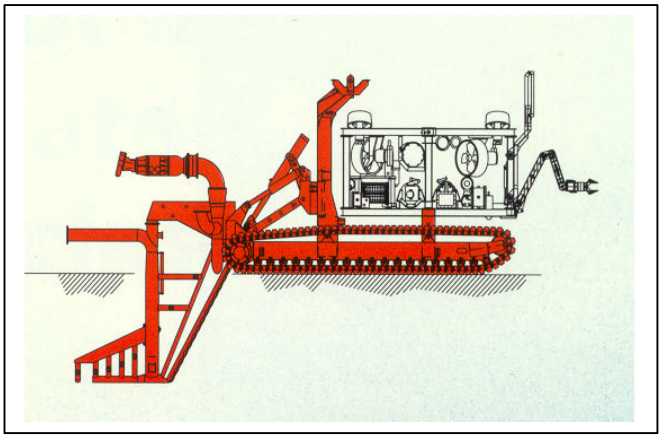
Perry Tritech's *Gator*™ II

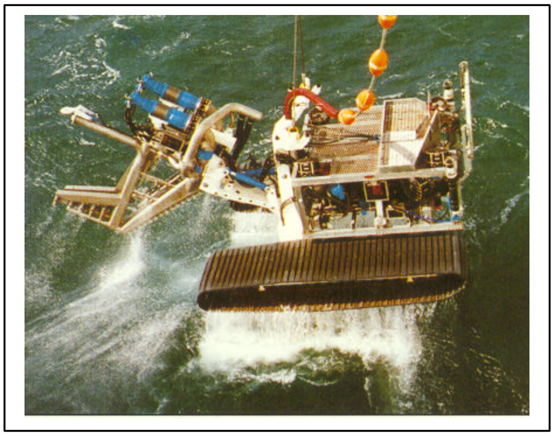
The *Gator* is modular, easily shipped, and can be deployed from vessels of opportunity. The vehicle's suite of trenching tools includes a water jetting unit for soft soils, a mechanical chain cutter for medium soils, and an earth saw for chalk and coral bottoms. *Gator* also features changeable track width options. Its 48-inch wide synthetic tracks allow it to operate on sea floors as soft as 7 kPa (kilopascals). Gator has recently been involved in installation of many of the shore end systems throughout Europe and Asia for the massive FLAG telecommunications system.

General Offshore's *Spencer* is a tracked shallow water vehicle designed to install cable in rock harder than 60 MPa. With two 500 hp hydraulic motors powering its tracks, this 47.56-ft (14.5-m) vehicle operates to water depths of 164 ft (50 m), limited currently by surface supply diver support operations. The blue-collar worker of the General Offshore artillery is its *Rocksaw*. Built in 1985, it weighs 45.5 tons, and cuts rock at 2,000 rpm with its 1,000-hp drive to a depth of 13 ft (4 m) and a width of 1.5 ft (0.45 m). General Offshore also maintains cable burial tools in the jetting blade configuration with injectors to fluidize soil and insert the cable at the bottom of the trench to depths in excess of 39 ft (12 m). The company's *Bantam* shallow water burial plow operates from inter-tidal zones to 164-ft (50-m) water depths, and can be used for post-lay burial.

Soil Machine Dynamics was founded through involvement in the burgeoning North Sea oil industry, which led to its current market niche–manufacturing cable trenching equipment for many of the largest corporations in the global telecom industry. Eight different SMD systems were recently utilized by three different installers in the FLAG project, and SMD plows have been used to bury over 18,645 miles (30,000 km) of cables requiring protection around the world, probably more than any other single manufacturer. The company manufactures sophisticated cable plows, seabed tractors, free swimming ROVs, and control systems. Its latest generation of cable plows is represented by Cable & Wireless' *Plow D* and McDermott's 9.8 ft and 13.1 ft (3 m and 4 m) trench depth cable plow. The plow incorporates an innovative steering mechanism that allows adherence to the planned cable route, independent of any variance on the part of the towing vessel due to drift, wind, etc. The plow is typically connected to the cable ship via three cables: the tow cable, the umbilical, and the fiber optic cable being buried. Rapid recovery in the face of deteriorating weather conditions is made easy, as the plow can be launched and recovered entirely on the tow rope.

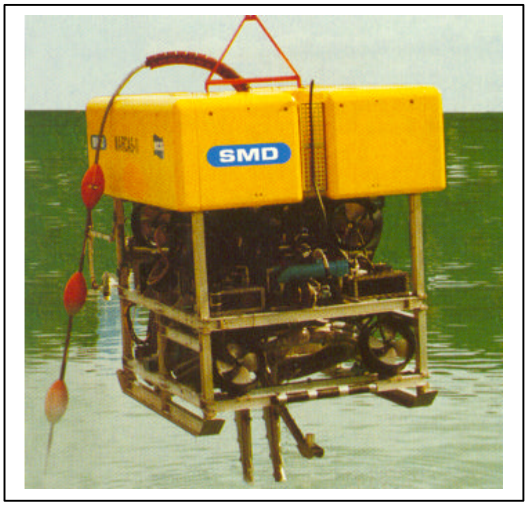
SMD was an early proponent of the seabed tractor to enhance cable installation, but there was a lack of paying customers for this technology. In the late 1980's SMD built its first cable tractor, *RT-1*, on a speculative basis. The gamble paid off, as AT&T (now SSI) ordered and received delivery of the first commercial tractor. BT Marine subsequently bought *RT-1* and renamed it *Subtrak*. SMD has sold newer, larger tractors to BT Marine, Stolt Comex Seaway, NTT and KCS. The new vehicles can accommodate three cable trenching tools: a robust rock wheel cutter, a chain cutter, and a jetting tool. All of these tools are capable of diverless loading and unloading.

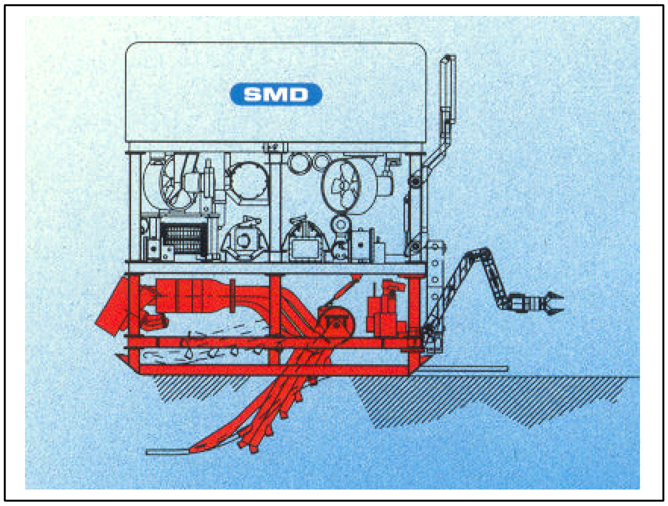




In 1993, SMD added a cable maintenance ROV (CMROV) to its product list. In designing the vehicle, they focused on thruster configuration. SMD worked on the assumption that most existing CMROVs are based on work class ROVs, which were designed for oil field intervention, retrofitted with a cable jetting package that results in poor positioning of thrusters for cable applications. To increase operator control, SMD's vehicle has a pair of thrusters positioned to counter the forces produced by water jetting. In "Jet Tool" mode this vehicle can excavate a 3 ft (1 m) deep slit trench and perform cable burial at speeds up to 3,280 ft (1,000 m) per hour. The ROV is rated for water depths up to 8,200 ft (2,500 m).

Examples of SMD vehicles are provided at the top and bottom of this page.





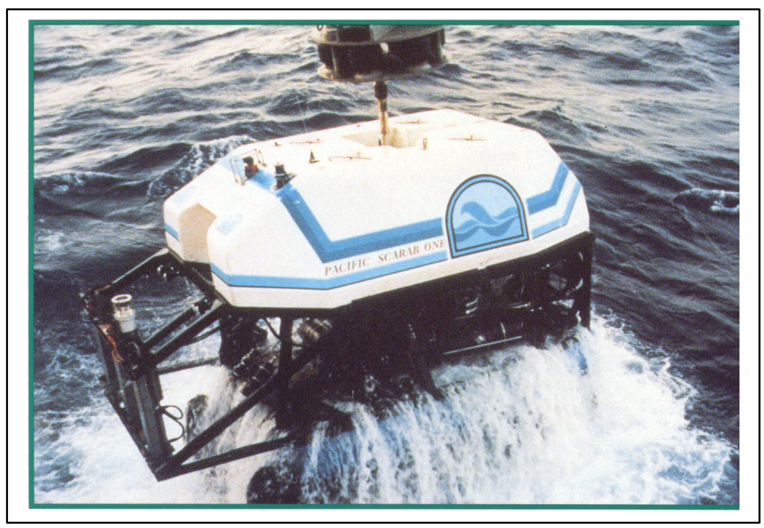
KDD subsidiary KCS purchased the first commercial SMD ROV, dubbed *Marcas-II*. With buoyancy and the jet tool removed, the ROV can be incorporated into a caterpillar-like tracked base when conditions require this configuration.

SMD's *MARCAS – II* (left)

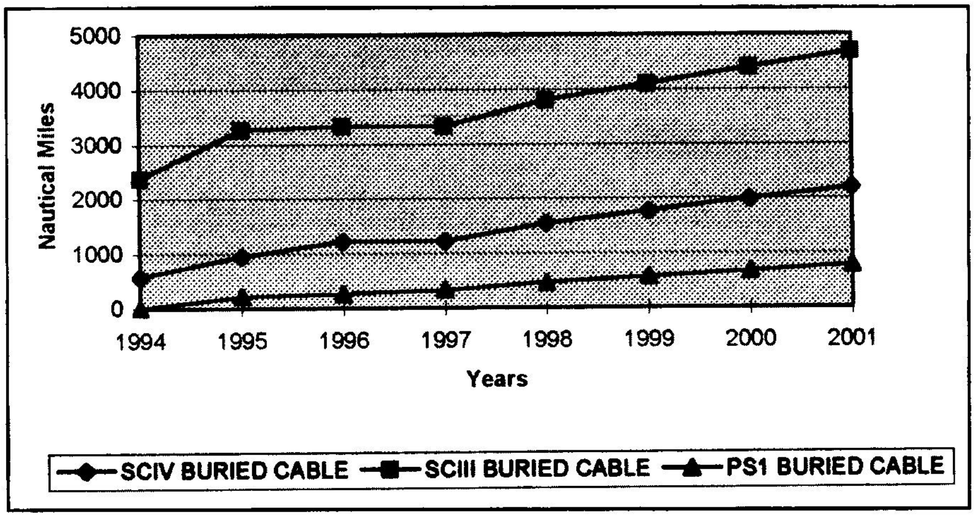
Cable Maintenance Agreements

In 1978, the Atlantic Cable Maintenance Agreement (ACMA) drew up a specification for the first generation of cable maintenance ROVs. AT&T Bell Laboratories answered with the AMETEK-Straza-manufactured *SCARAB-1* and *2*, rebuilt to the ACMA spec in 1980. (Around this same time, AMETEK's *Scorpio* became the world's most successful work class ROV). Slingsby built its *CIRRUS* vehicle in 1985 for Cable & Wireless to the same general specifications, the same year Perry constructed its *Triton ACMV* (Advanced Cable Maintenance Vehicle).

***SCARAB I* being recovered (right)**



In the April 1997 issue of *Sea Technology* magazine, Robert T. Bannon, of AT&T, provided insight into their cable maintenance agreements, supported primarily by the *SCARAB* vehicles. AT&T buries their cables approximately 6.5 to 8.2 ft (2 to 2.5 m) deep at the shore ends. Once out of the surf zone, the cables are buried to approximately 4 ft (1.2 m) until a depth of 3,280 ft (1,000 m) is reached. Where extensive offshore activity is encountered, such as fishing and dredging, the burial is continued to beyond the 6,560-ft (2,000-m) depth. The following tables provide additional information regarding the activity of the AT&T vehicles, along with their characteristics, in support to the AT&T maintenance agreements.



Linear forecast based of buried nautical miles of cable included in SCARAB agreements; SCIV = SCARAB IV; SCIII = SCARAB III; PS1 = SCARAB ONE.

SCARAB **Vehicle Burial Forecasts (Source:** ***Sea Technology*** **magazine, April 1998)**

Cable Maintenance Agreement Nautical Mileage (12/15/97)

Maintenance Agreement	**Total Miles**	**AT&T Maintainec**
Atlantic Ocean:		
West zone	35,030	20,846
East Zone	38,602	7,422
North Sea	4,942	799
Pacific and Indian Ocean:		
North American	8,454	8,367
Hawaii	11,314	11,314
Yokohama	19,641	10,225
Fiji zone	11,282	1,858
Southeast Asia Indian Ocean	30,617	
Mediterranean	13,321	
Total	**173,203**	**60,831**

(Source: *Sea Technology* magazine, April

AT&T Maintained Cable

Selected Maintenance Agreement ROV Characteristics						
Characteristic			**Vehicles**			
	SCARAB III	***SCARAB IV***	***ROV-128***	***SCARAB ONE***	***MARCUS II***	***CIRRUS-B***
Horsepower	180	150	180	150	240	100
Designer	Slingsby	ISE	Slingsby	ISE	SMD	Slingsby
Tool Design	Slingsby	Oceaneering	Slingsby	Oceaneering	SMD	Slingsby
Weight (tons)	3.8	3	3.8	5.25	3.9	3.3
Umbilical (meters)	2,800	2,350	2,800	3,200	3,300	1,200
Speed (knots)	3.1	3.5	3.1	3.9	3	3
Jetting Speed (m/hr)	600	520	100	560	1,000	100
Bollard pull forward (lbs)	1,325	1,500	1,325	1,700	1,700	1,325
Soil Shear Strength	200	100	100	100	100+	----
Soil elasticity (kpa)	High	High	High	High	Medium	----
Telemetry system	Slingsby	GESPAC	Slingsby	GESPAC	SMD	Slingsby
Cable Tracking	Slingsby	INNOVATUM	Slingsby	INNOVATUM	KDD	Slingsby
Cable locator	TSS	INNOVATUM TSS planned	TSS	INNOVATUM TSS planned	N/A	TSS
Cameras	3 x SIT	4 x SIT 2 color CCD	3 x SIT	4 x SIT 2 color CCD	5 x Cam.	5 x Cam.

(Source: *Sea Technology* magazine, April 1998)

Selected characteristics for AT&T vehicles used in support of their maintenance agreements is shown in the table above.

ACMA created a new specification in 1987, calling for more power and greater trenching capabilities, and thus was born the second generation of CMROVs. SMD and Slingsby answered the call with tracked "hybrid" vehicles, even though the ACMA specification strongly implied a straightforward, free-swimming vehicle.

Slingsby's vehicle consisted of a modular tracked base, outfitted with variable buoyancy, into which an ROV could be mounted. Cable & Wireless Marine and BT Marine adopted the Slingsby vehicle with *ROV 128* and *SCARAB-3*, respectively.

SMD's RT-1 was hired, and later purchased, by BT Marine.

Oceaneering International's free swimming ROV, equipped with a separate jetting package, was bought by AT&T Submarine Systems (*SCARAB-IV* Pacific *SCARAB-I*).

***SCARAB IV* during launch (right)**

Perry Tritech

Perry Tritech has developed cable ROVs that include the *Triton ACMV* and *Gator* systems, as well as two other systems. Perry Tritech's newest Cable Burial Work Package is the first self-contained work package that has been designed for use with an "ROV of Opportunity". The package can be powered by ROVs of 60 or more horsepower. Operators will be able to move the work package from area to area to be interfaced with various ROV systems (either hired or owned) located around the world.

The Cable Burial Work Package's jetting system has a counter-balanced design, which not only reduces the forces that would otherwise be applied, but eliminates the need for special thruster placement. Cable burial to 3 ft (1 m) in low shear soils (5-25 kPa, non-cohesive) can range from 492 ft (150 m) to several hundred meters per hour.

Perry's *Flexjet* series started as an embedded 100-hp *Triton* mounted on a lightweight tracked system with water jetting capabilities. Today's *Flexjet II* is a dedicated cable/pipeline trenching system with variable buoyancy and the capability to "fly"–ROV-like–to and around the work site. With a combined 400 hp of water jetting pressure, *Flexjet* has attained speeds of 2,214 ft (675 m) per hour. The system can operate in soil densities of up to 120 kPa (stiff clay) and has a variable trench width of between 4 inches and 29 inches (10 cm and 72 cm). Working depth is up to 1 150 ft (350 m). Sonsub International has utilized the *Flexjet II* for a number of repair and reburial projects in the North Sea and offshore China, some of which included mounting the *Flexjet* on a burial plow.

Perry Tritech has recently built a new generation of cable installation, burial, and repair vehicle, the *Triton XL 250* Cable Maintenance Vehicle, based on its 250 hp *Triton XL* heavy work class ROV. With a rated depth of 8,200 ft (2500 m), the vehicle has a force balanced, dual arm jetting system. Maximum trench Depth is 7.2 ft (2.2 m), with a trench width of up to 1 ft (30 cm).

Perry Tritech's *Gator* No. 2 was manufactured for fully diverless operation and delivered in 1997 to Korea Submarine Telecom (KST) along with the fourth *Triton XL 250* cable maintenance ROV (see earlier figure).

Oceaneering International, Inc.

Oceaneering International, Inc. recently completed construction of the *Sea Tractor*, a 250-hp system designed for the US Navy for burial of cable in a wide range of bottom conditions. This tracked vehicle has a jetter and rock saw, each of which will trench up to 3.3 ft (1 m) deep, and a chain excavator that will trench up to 7.2 ft (2.2 m) deep. The *Sea Tractor* features a crane manipulator with horizontal reach of 24 ft (7.2 m), and a lift rating of 9,061 lb (4,100 kg) at 5.9 ft (1.8 m). This versatile, rugged vehicle can operate on land or undersea to depths of 4,920 ft (1,500 m).

The 100-hp *Phoenix* is Oceaneering's latest mid-depth cable maintenance ROV, capable of post-lay inspection and burial, cable cutting and retrieval, and other tasks in 6,560-ft (2,000-m) water depths. The vehicle recently completed 74.6 miles (120 km) of post-lay burial to 3.3 ft (1 m) in the APCN and JASURAUS projects.

Oceaneering has also constructed three 250-hp Phoenix Cable Burial Maintaineering ROVs, each rated for 8,200 ft (2,500 m) operating depths. These systems use 125 hp for burying cables 4 ft (1.2 m) into the seabed.

Oceaneering also operates the cable plow, "Sea Dragon," which buries cables to 4 ft (1.2 m) in water depths up to 1,640 ft (500 m).

Margus Company Inc.

Margus designs, builds and operates 100 hp work class ROV systems custom designed and configured for submarine cable operations. These systems include two onboard jetting pumps, cable cutter and cable gripper, cable location/tracking system, and other peripheral equipment. Margus is currently utilizing its S2000 ROV Series systems for post-lay burial operations in the Mediterranean. Gus Dodeman and Bill Wall of Margus were both instrumental in the design and operation of the original *SCARAB* ROV system.

The Many Others

And, there are many other cable burial vehicle manufacturers such as Tecnomare, Venezia, Italy. Tecnomare has been designing, building and operating cable trenching vehicles since 1972. One example, their *TM402-C* cable and flexible pipe trenching vehicle (shown earlier in this section) can operate in up to 160 meters water depth with a trenching speed of up to 1,312 ft/hr (400 m/hr) in soil conditions such as soft rocks or gravel, clay or loose sand. The trench can be narrow and deep, from 9.8 to 15.7 in (25 to 40 cm) wide and 59 in (150 cm) deep.

Because the industry is so highly specialized, some contractors have demonstrated a trend of manufacturing or modifying their own tools. Conversely, some manufacturers work closely with (and within) contractor operations to improve the effectiveness of their designs.

Post-lay surveying provides assurance to the contractor (and the customer) that the cable was buried properly. Innovatum, Inc.'s ULTRA System (see Chapter 6) utilizes all known detection and tracking modes (AC, DC, Passive and Pulse). An array of multi-axis sensors and a sealed can of data processing electronics are mounted on the ROV and interfaced to a surface computer and video imaging system. The graphic display provides a 3-dimensional cross-section view of the area beneath the sensor array. Considering the obvious costs associated with underwater cable burial, the ramifications of not knowing where and how deep the cable is buried will always prove to be of great economic interest when maintenance issues arise.

High resolution portable sonar systems, such as those manufactured by Reson, Inc., are used by many operators to "view" the cable lay in process. "During the lay operation itself, high-resolution imaging sonar is used to monitor the operation and give plow operators ample warning of obstacles, changing seafloor topography, and the position of the cable relative to the trench," said Dennis Tivey, marketing coordinator of Reson. He adds, "Underwater acoustics play several roles in submarine cable installation–both in the lay operation itself, and in the pre-lay phase, where high resolution seafloor bathymetry allows engineers to determine the optimum route for the cable lay operation."

The Pre-Lay Survey

A thorough cable route survey is the proverbial "ounce of prevention" that can have a future impact measured in millions of dollars, both in the installation phase, and in prevention of damage and outages to the fiber optic system. Providing inadequate information to the installation contractor is the most common cause of cost overruns during submarine cable installation. There are many situations that can have an impact on the contractor's ability to do his job. The following list of factors which can negatively affect the selection of a cable landing site was compiled by Graham S. Evans, EGS Surveys, and James P. Byous, General Offshore:

- Difficulties achieving specified or adequate burial depth due to the presence of rock or coral outcrops, or the presence of excessively hard seabed substrate.

- Cable suspensions due to an extreme bathymetric profile or the presence of sand waves and rock or coral obstructions.

- Unsuitable seabed for the support of a burial vehicle, such as seabed obstructions, radical bathymetric profile or inadequate load bearing capacity of seabed soils.

- Excessive currents related to tidal flow or longshore drift, which can hinder both the landing and burial spread maneuvering.

- Long shore end pull from the lay vessel due to shallow, flat seabed profile combined with small tidal fluctuations. These factors dictate the mooring position of the lay vessel and can result in a long post-lay burial situation.

- Small tidal fluctuation, which hinders the ability to overlap land-based excavation equipment with the marine-based trencher, often resulting in a region of inadequate protection within the surf zone.

- Seasonal beach erosion or mobile seabed sediments cause burial depth to be compromised or cable re-exposure during the rough weather season.

- Obstructions on the route or interference of the installation operation due to fishing, tourism, or other industrial activity.

- The presence or suspected presence of ordnance at the landing site or route approaches due to previous wartime activities or the proximity of military exercise areas.

- The presence of other infrastructure along the route, such as telecom or power cables, pipelines, etc.

While deepwater cable lay and burial routes can usually be expected to have a lower incidence of difficulty factors, many of the situations above can also be encountered offshore. When an offshore installation contractor runs into problems, the economic impact can be very large, due to the operating cost of vessels and support for such an operation.

Datasonics (Cataumet, MA) manufactures a system aimed to fulfill the needs of cable route surveys, the SIS-1000 Seafloor Imaging System. C&C Technologies of Lafayette, LA, utilizes the equipment for cable route surveys. The SIS-1000 will be utilized as an open-frame design. Its standard configuration of chirp side scan sonar, chirp sub-bottom sonar, cesium magnetometer, pitch-roll-and-heading, pressure sensor and tracking beacon, will be augmented on the open frame by a Simrad 3000 multibeam sonar and a TSS 335B.

Cable Repair Operations

There are as many variables in a cable repair operation as there are cables. Most repairs share common characteristics that can be discussed in general terms. All repair jobs start with the cable operator's rude discovery that "the darn thing isn't working!"

Long-haul telecommunications submarine cables are powered by high voltage DC power plants, or power feed equipment (PFE), at each end, which furnish 8 to 15 kilovolts DC across the system at currents of up to 1.6 amperes. This electricity powers the system's repeaters. If a fault occurs, alarms at the PFE and the transmission station will immediately alert the cable operator of failure. Various methods localize the fault from the terminal to within one repeater section along the cable. Tone detection systems, such as those manufactured by Innovatum and TSS, can locate the fault within a few feet. Innovatum's Ultra cable location and tracking system employs four combination gradiometers and triaxial magnetometer sensors.

Perhaps the cable was kinked, or perhaps severed completely and ripped from its protective seabed for hundreds of feet in either direction. Anchor scars or distinctive trawler footprints sometimes disclose the cause of the trauma. Or, there may have been no trauma, and wave action caused the cable to seesaw against a sharp rock formation, wearing a small hole in the cable jacket. Then water seeps in, reacts with electricity from the power component that fuels the subsea repeater, causing hydrogen to form and eat away at the optical fiber.

The visual search for the damaged section will be performed by either a diver or an ROV, depending on depth and access conditions. When the fault is located, repair will require cutting the cable. This is usually accomplished through the use of a guillotine cutter. ROVs, which are configured for cable maintenance, will allow for this eventuality.

The Weddelli ROV, a *Triton XL6* design by Perry Tritech built for Asean Cableship (Singapore), has manipulators capable of reaching 4 ft (1.2 m) below the seabed. This allows use of the cable cutter and cable gripper below seabed level. Before cutting, a transponder is often placed for easy return to the site. One end of the cut cable will then be winched to the surface and attached to buoys for reclamation. The second end is then recovered from the seafloor, and an additional length of cable is spliced on to allow the cable to be rejoined topside.

Once the cable is returned to the seafloor, it is re-buried in a crescent pattern, allowing for the extra length that has been added. Free-swimming ROVs, the method of choice for most operations, are used to support this task. Seafloor maps and charts can then be modified to correctly depict the as-built cable route. As the fiber optic infrastructure ages, there will be even greater emphasis on maintenance operations within the submarine cable milieu.

Greater Capabilities, Increased Expectations

In a paper presented at Underwater Intervention 1996, authors Imlah, Reece and Matsushita state: "The telecom installation and maintenance market is moving in the same direction as offshore oil, that is from a friendly acceptance of best endeavors, to a potentially costly insistence on meeting specifications, no matter how arbitrary." This indicates a maturation of the market that, like the journey to adulthood, will be a painful process for some. A mature market will represent a bigger pie, but the risk/reward ratio may be pushed higher by more players vying for a slice.

As a maturing industry, submarine cable installation and maintenance may also see an increased push for standardization, and a healthy appetite for R&D budgets to increase job efficiency. The world of matter has, indeed, become a great nerve. Photons and electrons flood our senses with information and entertainment. As in the subsea oil and gas business, underwater contractors have become a relatively small, but incredibly important, niche player without whom the "Information Highway" would be a pothole-filled, horse-and-carriage sidestreet. And, as shown throughout this section, ROVs, from cable plows to sophisticated cable repair systems, will play an indispensable role.

RELIABILITY & MAINTAINABILITY

Due to operations in deepwater and the cost associated with these operations, manufacturers have had to produce very reliable and easy to maintain systems in order to avoid costly downtime offshore. It can take several hours for a vehicle to reach an 8,202-ft (2,500-m) depth. If a system failure occurs, an entire workday can be lost. Some operators require a redundant ROV to be aboard a ship or platform to minimize downtime.

For example, the following table shows Oceaneering's statistics from over 10,000 dives in water depths greater than 2,953 ft (900 m). All dives of 12 hours or longer have been deleted from the calculation to ensure that the times represent a "normal" dive. A normal dive takes approximately seven hours without any daily R&M (repair and maintenance). If the R&M is included, the "normal" working day extends to an average of almost nine hours.

The "Normal" ROV Dive Timeline

• Water Depth	5,413 ft (1,650 m)
• Deployment and Transit	2 hrs (Note 1)
• Average Time on Bottom	2 hrs 40 min
• Riser Inspection	4 hrs 30 min
• Transit & Recovery	1 hr 30 min
• Post Dive Checks	30 min
• Daily R&M	??
• Average Dive	6 hrs 40 min
• Daily R&M	1 hr 30 min (Note 2)
• Minimum Recommended Crew	3

Notes:
1. Includes pre-dive checks
2. Includes a thorough weekly umbilical inspection, electrical and optical fiber tests.

Oceaneering's deepwater ROVs, beginning in the early 1980s, have put a high premium on Maintainability and Reliability. As noted earlier, the round trip time from 8,202 ft (2,500 m) is on the order of 3 hours without any associated repair time. In 19,685 ft (6,000 m), round trip times approach 12 hours as it is simply not feasible to have the through water speeds possible in the shallower depths. In deepwater, reliability is of major importance. In fact, it exceeds performance in the final analysis. An ROV system that has less than optimal performance can, in the hands of an experienced crew, carry out all the work tasks. It may take a bit longer but the work gets done. An ROV system that has a key component failure can do no work whatsoever. In addition, recovering a dead ROV from deepwater is often a difficult task at best, with the recovery times being 2 to 3 times greater than an operational system.

Today, ROVs have become very reliable if maintained properly by trained crews offshore. A recent example of this is Sonsub International's *Triton XL* 8, which has recorded over 5,000 hours of dive time supporting activity on Shell Deepwater's Mensa field. Approximately 90 percent of the dives made by the ROV were made to depths of 5,112 ft (1,558 m) or greater. The vehicle operated in various critical path scenarios and often made extended dives of several days at a time without surfacing. This reliability extends from many years of producing and improving *Triton* systems along with major advances in technology.

CHAPTER 6. WHAT SHOULD I KNOW ABOUT?

This chapter begins with a general overview of the ROV along with key operational considerations for the offshore ROV from the point of view of a major offshore company. Following the introductory material, a more detailed discussion of the most critical subsystems and components of the ROV is provided.

MAJOR SYSTEM CONSIDERATIONS

System Design

The ROV system is a highly interrelated group of subsystems that, when functioning synergistically, provides an impressive subsea capability. Since the characteristics of the vehicles are multi-variant, with no unique solution, the design process is necessarily iterative. Because of this highly interdependent relationship, ROV system performance is a delicate balance of design and operational characteristic tradeoffs. The system can be arbitrarily divided into a number of major subsystems. These would generally include:

- Vehicle
- Tools and sensors
- Control/Display console(s)
- Electrical power distribution
- Umbilical and tether cables
- Handling system

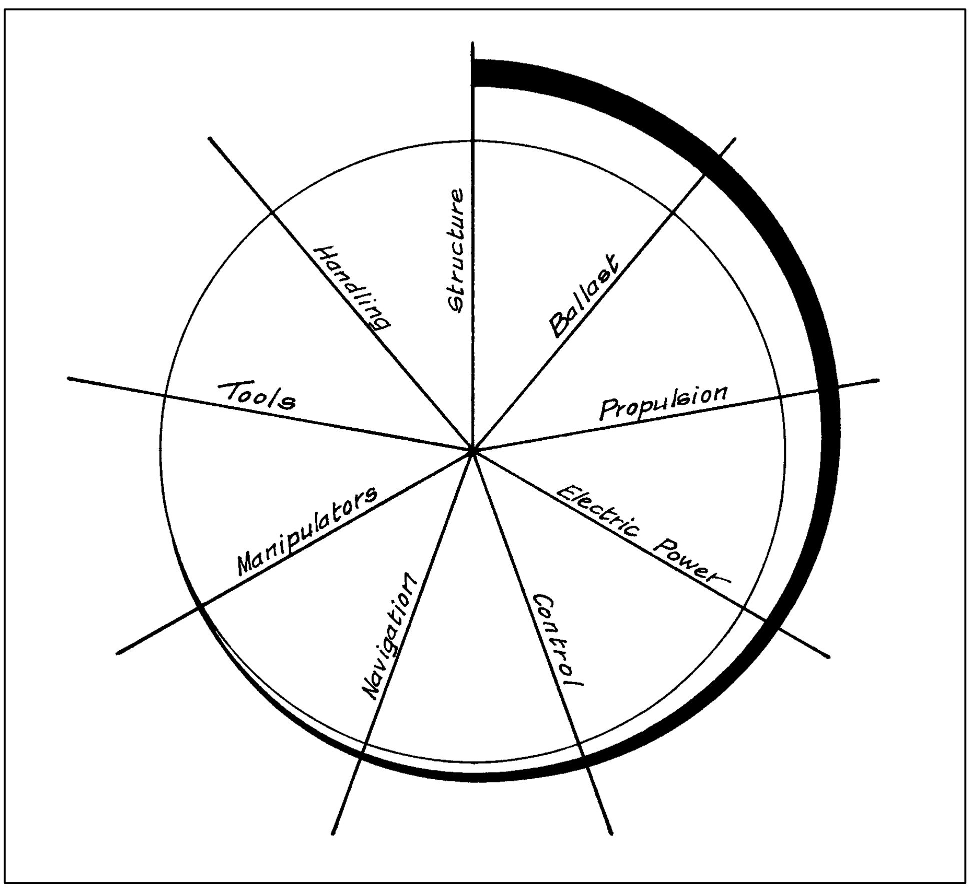
There are grey areas at certain of the subsystem boundaries. For example, does the umbilical belong under electric power, control or handling subsystems? Clearly, some assignments that will follow are arbitrary. Other considerations that drive many of the subsystem interelationships include questions such as:

- Open-Frame or Monoque
- Electric or Electro-hydraulic power
- One HPU or two HPUs (redundant)
- Power to thrusters vs. power to work packages
- Fixed or variable buoyancy or both
- Fiber optic vs. conventional telemetry system
- Movable lift point vs. fixed

The vehicle may also be further subdivided for convenience into functional subsystems. For example, a typical subdivision of the vehicle might be:

- Structure
- Ballast
- Propulsion
- Electric power
- Control
- Navigation
- Manipulators

The interrelationship of such subsystems is graphically illustrated in the "design spiral" shown in the following figure. An operator desires a modest increase in the speed capability of an ROV to maneuver in a current condition in a particular geographic area. The additional speed desired will result in the need for additional electrical energy and may generate the need for changes in the thruster/propulsion subsystem. Additionally, the configuration, structure, weight, control system, umbilical/tether size, tether management system, winch, handling system and power supply will all be affected.



The “Design Spiral”

Clearly, all of these subsystems and components are affected by what was a seemingly innocuous performance improvement desire. Thus, the user/operator is well advised to be aware of the ROV system's sensitivity to change and carefully consider the serious ramifications of contemplated field changes to what may appear to be minor components. The desire for small improvements in performance or the failure of a "minor" component will often have ripple effects through the entire system.

Today, with the aid of advanced computer design techniques, the modern ROV has evolved through many iterations of the design spiral. Today's ROVs are relied upon to perform complex operations offshore, in ever increasing water depths, and have accordingly reached a high level of technical design. These vehicles must also be flexible, that is, they must be capable of being configured for many tasks. This holds true for small and large systems, which are used for a variety of inspection and/or work tasks. Since the goal of the ROV is to accomplish an often-complicated task, its overall capability is usually driven by two major considerations–work requirement and operational water depth–both of which drive the considerations of the design spiral discussed above.

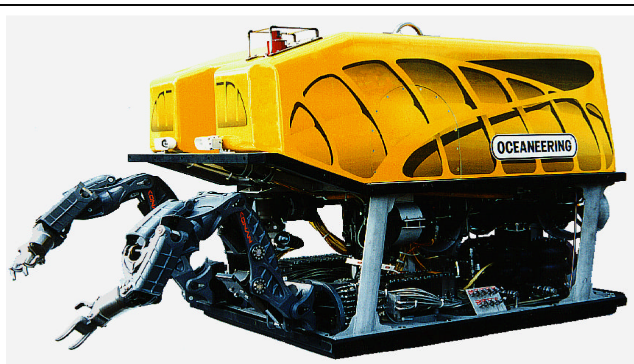
In addition to the basic categories above, there are a large number of considerations that must be made both in the design and in the selection of an ROV system such as:

- Cost
- Market size, requirements and acceptability
- The operational platform (e.g. ships, rigs, platforms, etc.)
- Current technology available
- Power
- Size
- Weight
- Deck space required
- Maximum depth
- Maximum sea state
- Payload capability
- Application
- Versatility (i.e. configurability for different tasks)
- Safety
- Reliability
- Track record (if any)
- Maintainability
- Field support and spares
- Warranty
- Subsystem interfaces and options available

System Categories

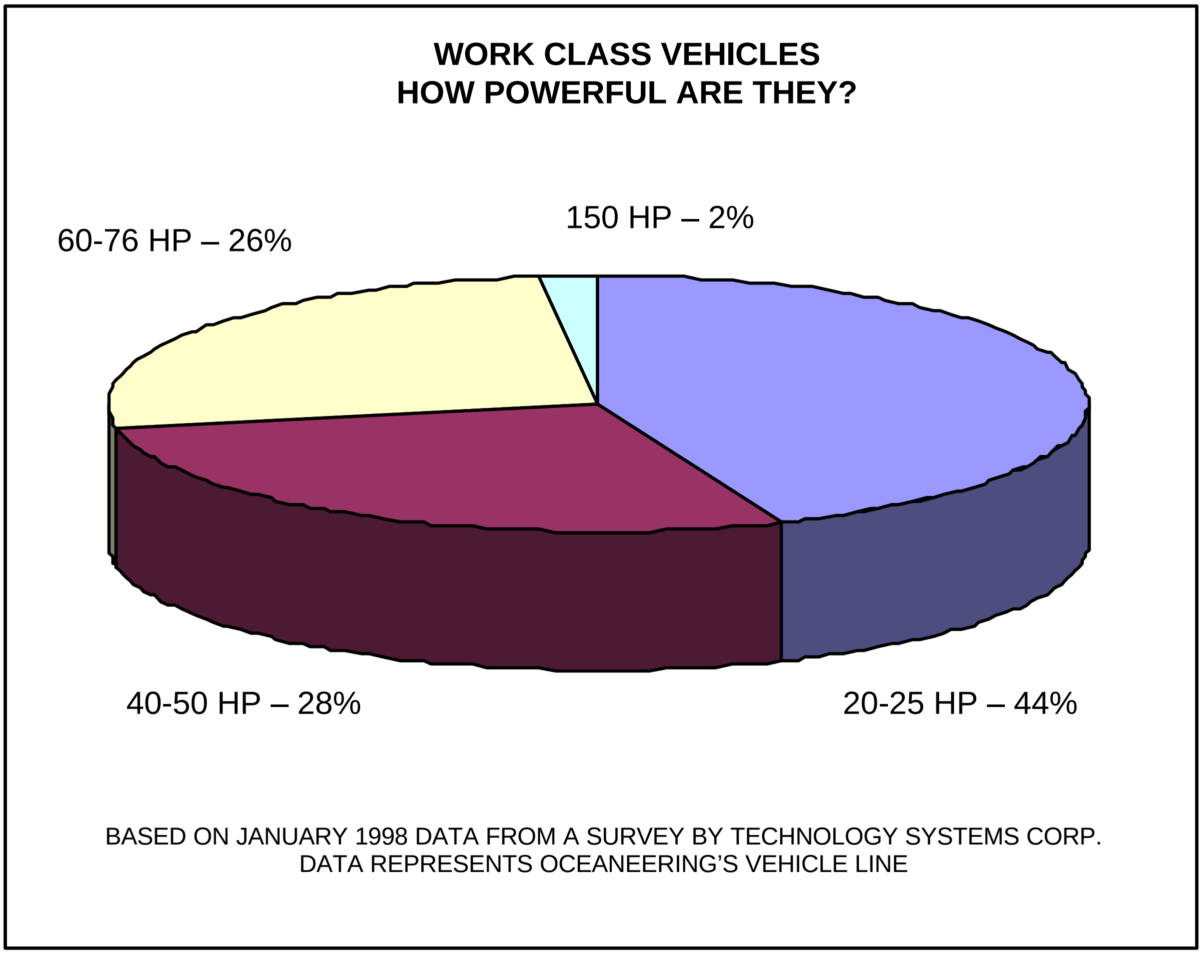
Modern ROV systems can be categorized simply by the following:

Class	Capability	Power (hp)
LCROV Electric	Observation (<100 meters)	<5
Small Electric	Observation (< 300 meters)	<10
Large Electric	Observation/Light Work(< 3,000 meters)	<20
Ultra-Deep Electric	Observation/Data Collection (>3,000 meters)	<25
Medium Electro/Hyd	Light/Med Heavy Work (<2,000 meters)	<100
Large Electro/Hyd	Heavy Work/Large Payload (<3,000 meters)	<300
Ultra-Deep Electro/Hyd	Heavy Work/Large Payload (<3,000 meters)	<120



(Clockwise, from top left)
***Phantom* – electric vehicle,**
***Viper* – light work class,**
***Triton XLII* – heavy work class,**
***Magnum* – work class ROV**

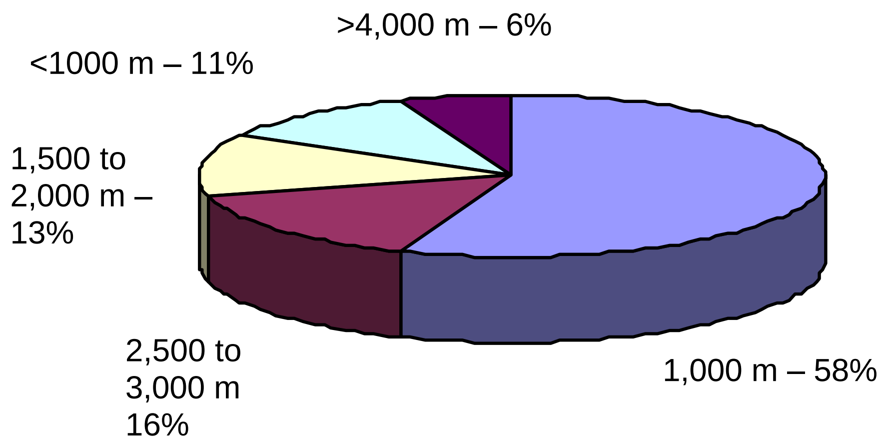
Ultra-Deep ROVs have been used extensively for science and deep ocean salvage work (funded primarily by the military) for many years, however, these systems were very expensive and purpose-built to perform a specific task and were often kept low power (usually <25 hp) to minimize umbilical size and weight. For comparison, the following table presents the percentages of work class vehicles and the amount of horsepower they have.



Work class vehicles – how powerful are they?

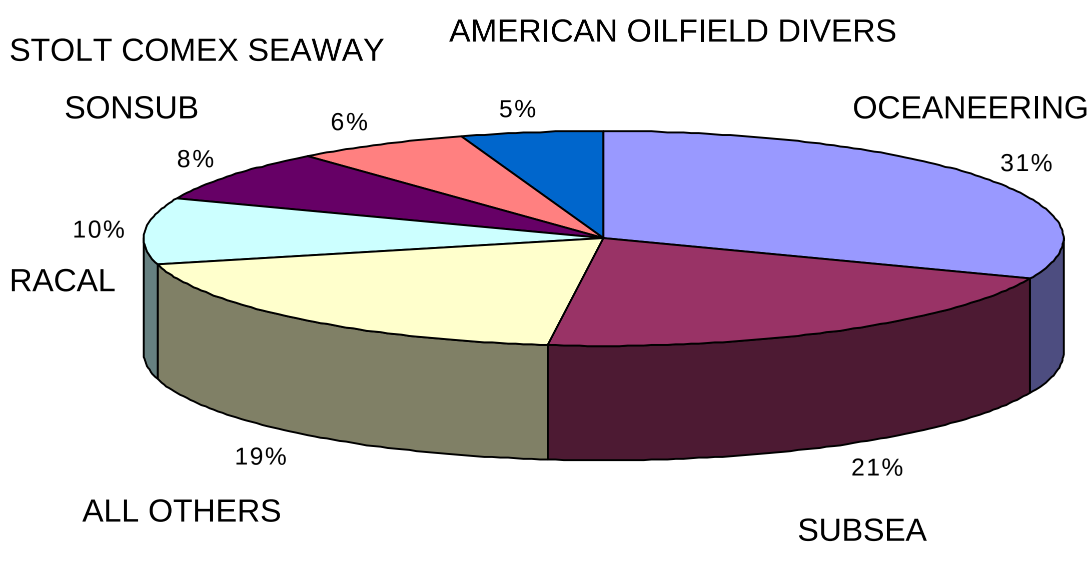
The following page presents additional information on the depth capabilities of work class vehicles and which companies are operating the highest number of work class systems.

DEPTH CAPABILITIES
OF WORK CLASS VEHICLES



BASED ON JANUARY 1998 DATA FROM A SURVEY BY TECHNOLOGY SYSTEMS CORP.
REPRESENTS 299 WORK CLASS VEHICLES

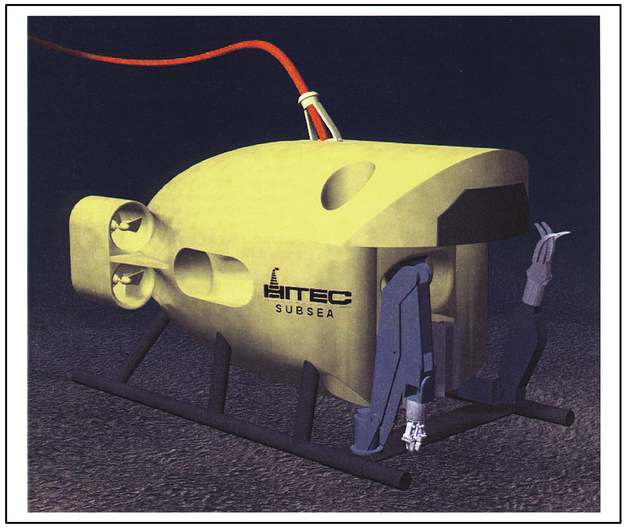
PERCENT OF WORK CLASS VEHICLES



Based on January 1998 data from a survey prepared by Technology Systems

A new class of Ultra-Deep ROV has recently emerged to support the oil and gas industry in deepwater exploration, drilling and installation. Unlike its predecessors, these systems must have plenty of power (>100 hp) and be capable of performing complex, heavy work tasks in high current conditions. This class of vehicle has, in one case, re-introduced the monoque approach to the overall vehicle design in an attempt to make the ROV more streamlined and capable of working in higher currents. This is contrary to the open-frame approach that most designers prefer, enabling easier access to components for maintenance and repair. The contrast in designs can be seen between the Perry Tritech *Triton ST* and Hitec *Stealth* ROV shown below.

Perry Tritech's *Triton ST*



HITEC Subsea's *Stealth*

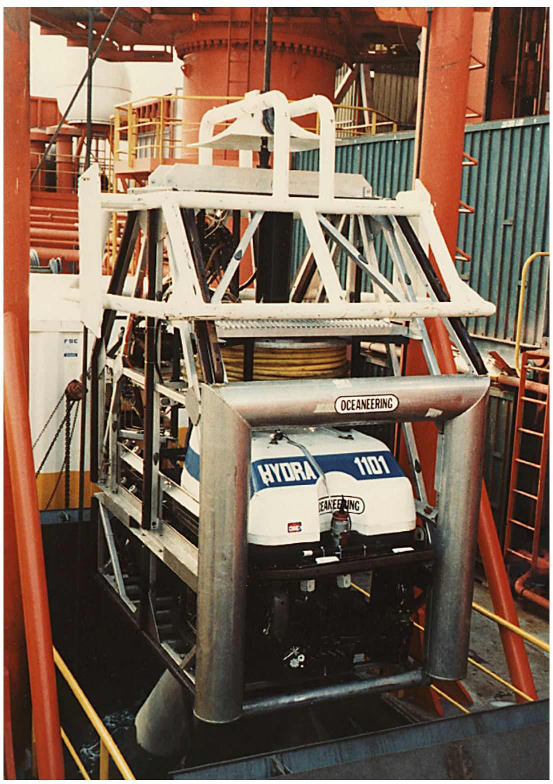
Support Systems

Another major change has occurred in ROV system design in the area of tether length, which will drive the overall ROV support system. Where 328 ft (100-m) ROV tethers (from the TMS to the ROV) were common earlier, lengths to 656 ft (200 m) are now common. A departure from the traditional tether design has been seen recently in applications where ROVs are being used to observe post-lay performance from cable laying ships. In such applications the ROV may be required to be at the touch down point over 3,281 ft (1,000 m) behind the ship. For this application, designers have provided a heavy tether, versus the traditional neutral tether, to reduce the diameter and allow up to 4,921 ft (1,500 m) of tether to be installed on an existing TMS. This allows the ROV to reach the touch down point of the cable or pipeline it is to observe.

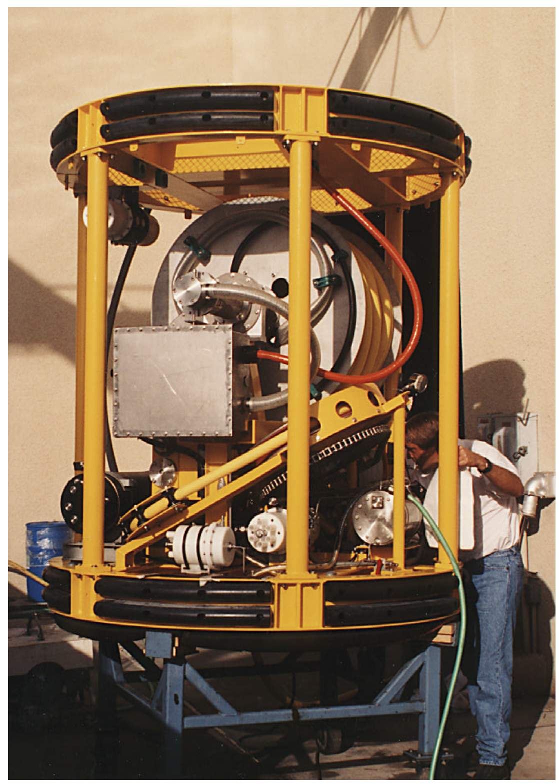
Some of the major design tradeoffs that must be made for ROV support systems include:

- Tether management system (TMS) vs. umbilical
- Side-entry vs. "top-hat" TMS
- Short vs. long tether
- Traction winch vs. conventional winch (umbilical)
- A-frame vs. crane for launch and recovery
- Stern vs. side vs. through moonpool launch
- Voltage vs. umbilical requirements
- Steel vs. Kevlar umbilical

Examples of several configurations are shown in the figures that follow. And, in the next section, a major offshore company–Canyon Offshore Inc.–highlights additional key areas of concern.



Side Entry (Cage)
Tether Management System



"Top Hat"
Tether Management System

A-Frame style launch and recovery system (right)

Crane (over-the-side) launch and recovery system (below)

The ROV Offshore - System Considerations

The design and reliability of unmanned underwater systems have come a long way since the US Navy first introduced the immature robots in the early 1970s, followed by their slow acceptance into the offshore industry. Today there is a wide range of ROVs available and the potential user must ensure that the system he is using is dedicated to the end application. Canyon Offshore Inc., one of the fastest growing ROV operators, offers the system considerations that follow in this section. One cannot use a "flying eyeball" inspection system to do a work class vehicle's job; and vice versa would be a waste of good money. A good example of the range of systems available to the user is provided in the adjoining figure.

ROVs come in a variety of sizes (right)

When working offshore, especially in the Gulf of Mexico, the typical ROV system will include the following characteristics: will be caged, or use a tether management system (TMS), be deployed by a launch and recovery system (LARS) and will have a minimum of a 2,000 to 3,000 ft (610 to 914 m) working depth.

- **LARS deployed**
- **TMS or caged**
- **2,000 - 3,000 meter depth rating**

The overall ROV is a complex system, and there are several aspects of the system design that must be taken into consideration. This section will investigate some of the more critical system aspects such as:

- **Available horsepower**
- **Through frame lift**
- **Electrical control**
- **Working envelopes**
- **Grab rails vs. docking**
- **Manipulator configurations**
- **Colors & labels**
- **Buoyancy**
- **Deployment and recovery times**

The following sections will address these critical subsystems.

Available Horsepower

The days of unreliable ten horsepower motors and ROVs with limited range and strength are long past. Today's vehicles are high power systems–if needed–with almost astonishing reliability. As discussed elsewhere in this publication, modern day ROVs may work for weeks on end without a failure–as long as proper care and maintenance is performed on the systems. This will be discussed later. However, if high power is needed, then the user has the ability to choose ROVs with power ranges from 50 to 100 horsepower…and higher.

When considering the topside power, don't forget that most of modern day ROVs are operated hydraulically, which means that electrical power must be converted to hydraulic power. This will cost the operator about 20 percent of electrical power going into the umbilical, although resulting in more compactness in the vehicle.

One of the added benefits to the high power subsystems installed on ROVs is that there is plenty of power available for other than flying the vehicle around and fighting the often far from pleasant underwater environment. Modular systems are designed that provide up to one-third of their available power on site for intervention tasks. Remove the problem of maneuvering the vehicle and fighting local currents by docking with the object that is being worked on and much higher levels of power can be channeled toward the underwater task at hand. For smaller ROVs that are only performing inspection tasks, lower power requirements are acceptable; just ensure the environment matches the maneuverability expected of the vehicle, and that includes the expected cable drag in the worst case currents expected at the work site.

- **Work class ROVs are 50 to 100 hp+ (electrical rating)**
- **80% conversion to hydraulic hp**
- **80 hydraulic hp equals 45.7 gpm @ 3000 psi**
- **2/3 of hydraulic hp reserved for ROV operations free flying**
- **1/3 for intervention tasks**
- **Higher levels available for Intervention if docked**

Through the Frame Lift

Heavy-duty work and recovery systems are designed from the bottom up with their final lift applications in mind. Many systems are designed to handle significant weights directly attached to their frame. Now, you wouldn't expect the ROV to "fly" to the surface with a 10,000-lb (4,535-kg) object hanging below it, however, if that was the final application, then the vehicles can be designed accordingly. When designing for such applications, whether it is lifting a wellhead in the oil field or a lost plane from 20,000 ft (6,096 m) in the ocean depth, the overall system must be taken into consideration. That means including the LARS, TMS, ROV, and the method of handling cable motions at the ship. The frame of the ROV and all components that interact with it must take these factors, which include actual weight, dynamic loads, virtual mass, etc., into consideration, or your system will end up on the ocean floor along with the object that was being recovered.

These all add up and can result in a very substantial vehicle and handling system–and operating platform to go with it. And, ensure that the final step is taken into consideration–transferring the load from the vehicle to the surface in what might be a rather heavy sea state. Getting an object to the surface is the easy part, getting it through the surface onto the ship is the hard part–this has proven to be the case time and again. System design–the overall system–is omnipotent.

- **Determine total weight of additional intervention components on the ROV**

- **Through frame lift figures allow for acceleration factors due to vessel motion**

Electrical Control

The structure, hydraulics and handling of the vehicle system can lead one into a design range where the electrical power can become the driving force. Just because you specify a cable and design an electrical system doesn't mean it will match the overall system requirements, interface properly with the operating platform, or, in some cases, be able to be manufactured. Providing available power to the vehicle can become an incestuous loop–as the power increases, the tether diameter grows, driving the needed power at the vehicle, which increases the tether…

All system aspects need to be considered–from platform interface to control consoles and telemetry, and from tether design to the ultimate power necessary at the ROV.

- **How much spare vehicle**
- **Limited by tether**
- **How much DC and AC power is available**
- **DC voltages are normally 24 or 28 VDC**
- **AC voltages normally at 115 VAC 60 Hz**
- **Spare console I/O is limited**
- **Vehicle connector's availability is limited**
- **Telemetry systems may be limited**

Working Envelopes

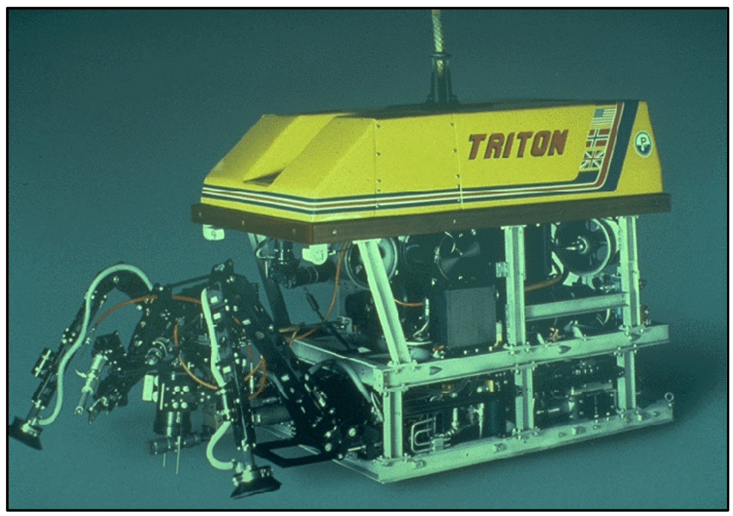
The design of manipulators and work systems is discussed in more detail in other sections of this publication, however, there are some basic considerations that must be taken into account when planning work, whether on pipelines or offshore platforms. One of the most important is the actual working envelope of the manipulator. The ROV provides excellent maneuverability, and in many cases it becomes the next best thing to a "flying hand." However, in most cases, the actual working geometry of a manipulator is the limiting factor; this geometry can also be changed by the placement of a tool or other piece of hardware in the manipulator's hand. Once again, an overall system design that matches the actual mission is critical.

Today, with the advent of advanced computers that can store the designs of entire structures in their memory, the ability to automate tasks will soon be at hand, however, the basic method of operation is still via an operator using one or more cameras.

Bottom line–if you can't see it, you can't work on it. Camera positions, viewing angles, lighting considerations, etc., must be taken into account during the system design. The operator must be able to view the entire work envelope of the manipulator/tool system and have proper lighting cues to allow him to efficiently perform the task at hand.

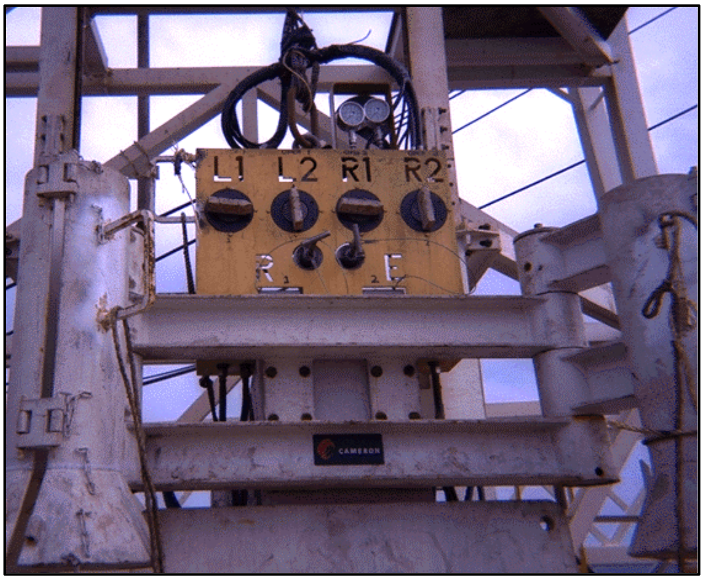
With proper design of the underwater hardware being developed, while taking into consideration the remote installation and maintenance of such equipment, the ROV operator's task can be made much simpler. The days of users designing systems with total ignorance of the ROVs that will work on them are slowly becoming a thing of the past. With that, the underwater equipment being installed is made to allow docking of the ROV at the most critical places. Free-flying the vehicle while trying to perform a complex underwater task in adverse environmental conditions is not the operator's first choice. Properly designed docking systems eliminate such concerns.

- **Operating envelopes depend on manipulator geometry and configuration along with camera field of view**
- **All manipulator tasks require visual feedback**
- **Stable vehicles simplify manipulator operations**
- **Pitch and roll do not help the operator**



Grab Rails vs. Docking Cones vs Suction Pads

There are several possible manipulator configurations available when considering vehicle design. The manipulators can be dedicated to work tasks, or in some cases, can be used for attachment of suction cups, or other such attachment methods. In most cases the ROV will have two manipulators and depending on how the underwater structure has been designed for ROV interface, the use of these arms can become limited. Using one manipulator to hold on while the other is used is probably the most undesirable, although better than free-flying the vehicle. Arms that can be moved to attach suction pads are a great improvement, but this increases the complexity. The best overall approach is the use of a docking cone or other similar device that leaves all vehicle manipulators free to manipulate–the capability that manipulator developers have put decades of design and millions of dollars into providing. Using a dexterous, force-feedback manipulator to hold onto a grab rail is a waste of its capability.

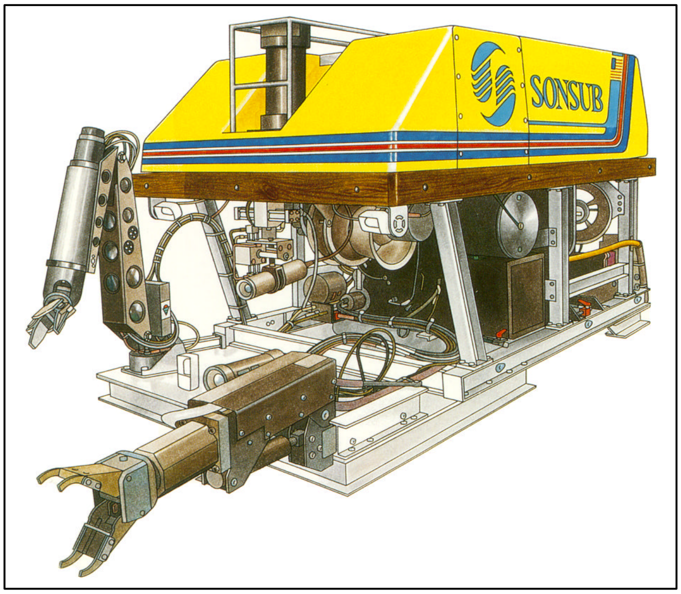


- **Grab rails allow ROV movement - one manipulator is unavailable**
- **Docking cones allow no movement - all manipulators are available**
- **Suction pads allow ROV movement - all manipulators are available**

Manipulator Configurations

As just described, the usual configuration is to use two manipulators on the ROV. If one of the manipulators is designed for more strength, and has fewer functions, it is usually called a grabber. And, since most operators are right handed, it is usually best to place the more dexterous manipulator, along with its controller, on the right side.

- **Ideal combination is a spatially correspondent arm and a grabber**
- **Spatial to starboard; grabber to port**
- **Spatial manipulators require hydraulic fluid and electrical power**
- **Grabbers utilize vehicle hydraulic functions**

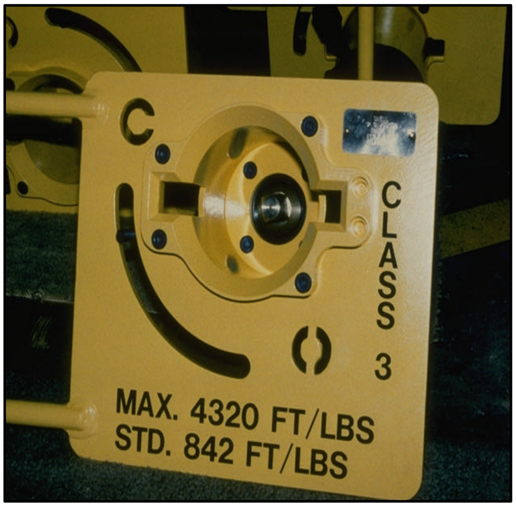


Manipulators have finally come of age and are providing much sought after reliability. Because of their compactness relating to available power, work manipulators are hydraulic. Although some of the earlier versions were all electric, they were either too bulky, inefficient, unreliable, or–in most cases–a combination of all three. However, the future application of autonomous vehicles that are operating under computer control may see a return to the electric manipulator. That technology, along with computers and electronics, has progressed to become a viable option for specific cases. Today, however, will be ruled by hydraulic manipulators; systems which have become of age.

Colors and Labels

In the topic of colors and labels, a picture is really worth a thousand words (and maybe thousands of saved dollars). You have to be able to see your target properly or you can't work on it efficiently. The following two photos and notes tell it all.

- **White is not a desirable color**
- **Yellow is the best color**
- **Labeling should be black on yellow**



- **Flame cut letters work well**
- **Shiny surfaces should be avoided**
- **BIGGER IS BETTER for letters and numbers**

Buoyancy

Buoyancy material, usually syntactic foam, provides much more than the colorful upper level on ROVs. Its integration with the overall system is critical to the proper operation of an ROV. For larger vehicles, such as the one in the following figure, its location is straight forward–on top; however, for many smaller vehicles, the positioning is not so easy since there is not as much room to work with. Its location must be high enough to provide a proper separation of the CG and CB (center of gravity and center of buoyancy). If the CB is not sufficiently higher than the CG, then the vehicle may not be adequately stable. In the case of larger systems, where space is not so limited, this problem essentially disappears. What does appear is the need to ensure the vehicle is trimmed properly–usually in a state that makes it slightly positive. By being slightly positive it allows the vehicle operator to use a slight down thrust to maneuver close to the bottom, thus preventing the thrust from stirring up too much sediment. If the operator is always thrusting down to stay above the sea floor, it won't be long before he can't see much of anything through the increasing turbidity. And, more in the old days than today–with much more reliable vehicles–the positive buoyancy allows your ROV to come to the surface for recovery once you have lost it, for whatever reason. Hopefully, the positive buoyancy of the system will be such that it will make it through the thermocline and not become trapped below it, which has happened in previous recoveries.

- **ROVs are normally configured slightly positive and level**
- **A work skid should be configured for neutral and level trim**
- **Buoyancy is the largest component in a work skid**

Today, offshore work vehicles are designed to carry attachable work skids, which should be designed as a neutrally buoyant module that does not effect the overall operational design of the primary vehicle.

One last item, for those of you who plan to use your vehicle in a fresh water environment, for whatever reason. The density of fresh water is less than seawater, thus the weight of the water displaced by the vehicle will be less. The bottom line is–your vehicle will sink in freshwater–as will a neutrally buoyant cable. Be prepared to add buoyancy and deal with a new operational configuration of your cable.

Deployment and Recovery Times

Working offshore is far from a benign environment, and ROV operations will be conducted in all conditions and sea states. In addition, the cost of down time for offshore operations can run around $10,000 per hour for starters. When considering that an average dive offshore lasts around seven hours, the time to launch and recover a system becomes very important, especially when the drilling operations are going into much deeper waters. A negative buoyancy system, using a heavy top hat or tether management system will usually get down faster than a free swimming, neutrally buoyant vehicle, that is using its own thrust, under constant operator control, to reach the site. In addition, the reliability of the system becomes critical–you don't want to begin repairing the vehicle when it is needed for an emergency.

- **Free swimming**
- **TMS / top hat**
- **Increasing depth means increasing round trip times**
- **4 Hours will be typical at 10,000 ft (3,048 m)**

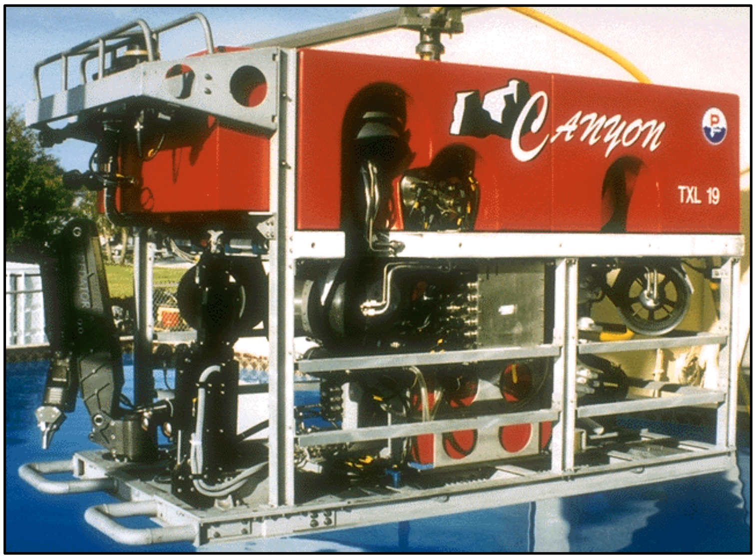
Deepwater Intervention

Deepwater intervention today is a far cry from the days when there was no interaction between the ROV developers and the offshore firms. Today, the lack of compatibility between the vehicle, and the tasks it is capable of performing, is beginning to disappear as the ROV is becoming an integrated part of the planning process. However, the vehicle is still limited in what it can perform. Thus, the interaction between it, the platform or subsea production system, and the skids and/or tools it will use to perform the work must be taken into consideration in advance. The vehicle can provide excellent dexterity with its manipulators, acquire and use specially designed tools, connect couplers to activate hydraulic systems, and so on. Advance planning for these tasks will allow the ROV system to perform them in as simple a fashion as possible.

- **ROV considerations**
- **Tooling skids**
- **Subsea acquired tools**
- **Fluid transfer**
- **Manipulator and torque options**

Basic ROV Intervention Components

The work subsystem of the ROV has become very capable. Modern manipulators and grabbers, like the ROVs themselves, have become efficient and reliable. Manipulator lift to weight ratios are increasing, positioning capability is becoming more accurate, and the tooling is better and more efficiently designed. The knowledge of offshore operations is being placed into effect with “ROV friendly” rigging hardware being designed, such as padeyes and shackles. In addition, with the higher quality of umbilical cable design, and higher bandwidth provided by fiber optics, the availability of multiple TV and camera views has increased to a point where the operator no longer has to feel like a horse wearing blinders. But, although the technology is available, without proper system integration it will just go to waste.

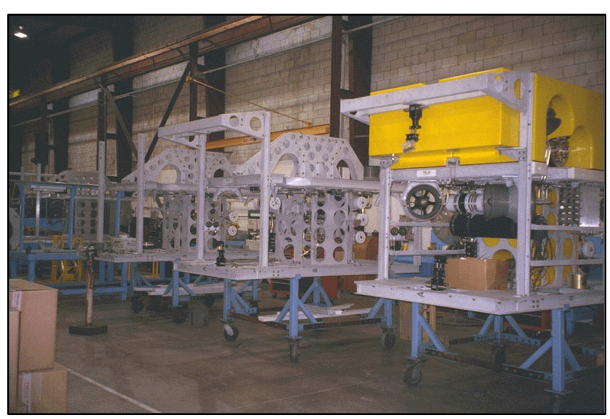


- **Video cameras**
- **Still cameras**
- **Manipulators**
- **Hot stabs**
- **Torque tools**
- **Hard/soft line cutters**
- **ROV friendly hooks & shackles**
- **Dredges**
- **CP probes**
- **Sonar**

Tooling Skids

The addition of tooling skids to ROVs has provided the next step in logical system integration. There is no vehicle that can do all things–contrary to the goal of early ROV developers who failed miserably in trying to produce such beasties. The removable skid allows the primary vehicle to be reconfigurable for various operations, along with being a simpler system when only performing visual inspection or other less complex tasks. Vehicles have been designed to allow the tooling skid to be as complex as an underwater trencher. The primary consideration is that the new skid must follow the same system integration considerations that the ROV had to follow earlier. The interface between the ROV and the skid must be taken into consideration when the ROV is developed, and the interface between the skid and the system it will work with is just as critical.

- **Skids vs. vehicle integration**
- **Materials**
- **Limitations**
- **Component selection**
- **Testing considerations**
- **Control options**



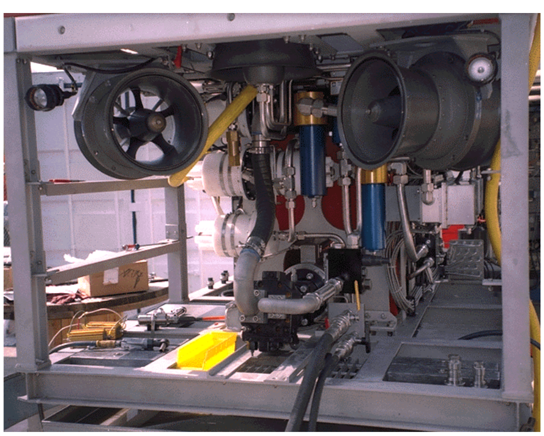
Subsea Acquired Tools

Another option, when it comes to getting the proper tool to the necessary location, is the aspect of subsea acquired tools–equipment or tooling that is placed on the seafloor ahead of time. These modules, or tools, must be designed with the previous considerations also in mind, and may add several benefits for the ROV design. Without having to carry the tool or skid as part of the ROV system, the overall size, weight and complexity of that system can be reduced. If the tool is put in place while the ROV is operating, then an additional deployment system may be required. The following should be taken into consideration when using subsea acquired tools.

- **May require additional deployment system**
- **Removes weight and stack height constraints**
- **Normally requires hot stab and/or electrical stab operations**
- **Neutral buoyancy and level trim are good practice**
- **Suitable for use by an ROV of opportunity**

Fluid Transfer

Whether using the ROV, a tool skid or a subsea acquired tool, the following should be kept in mind when working with subsea fluid transfer.

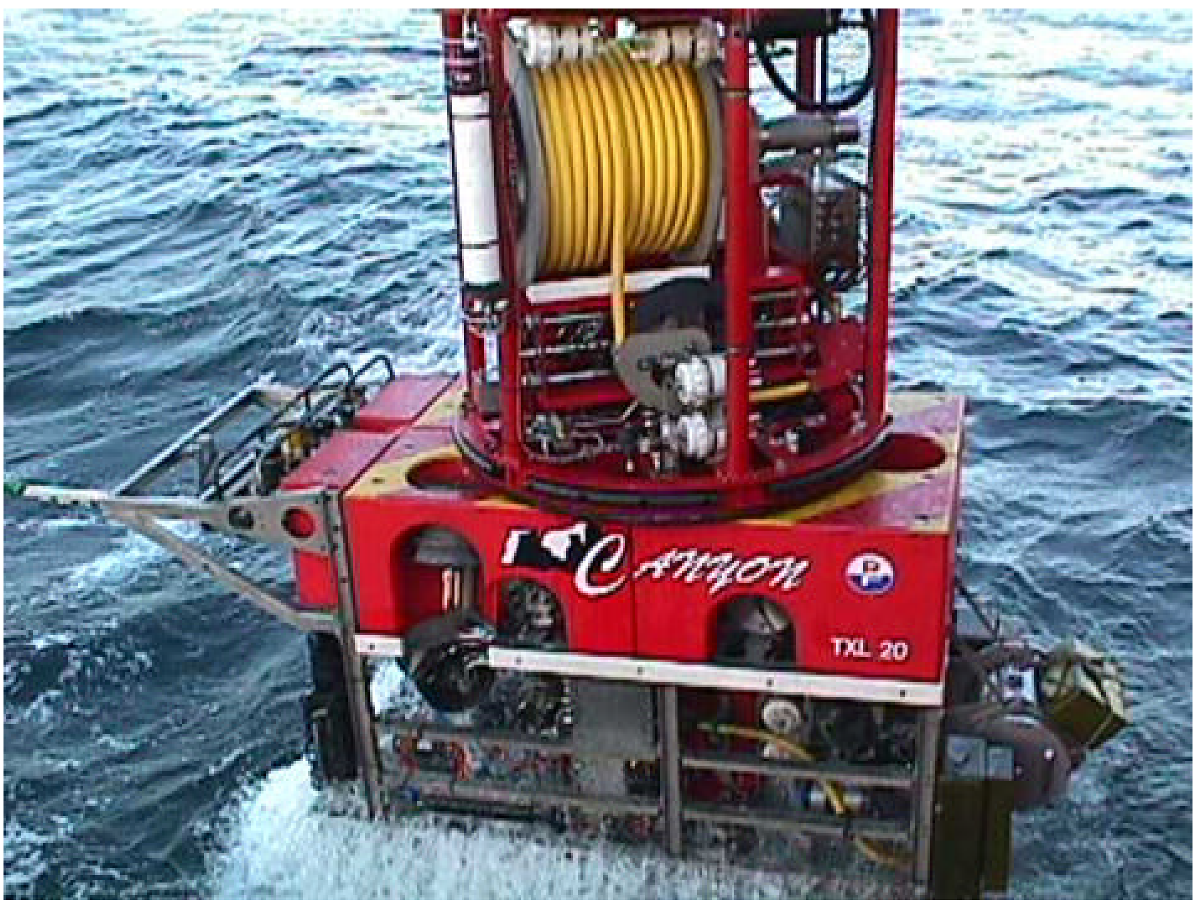


- **Hydraulic pressures may require 10,000 psi and higher**
- **Flow rates at high pressure are low**
- **Pressure and directional control of high pressure low viscosity fluids costs money**
- **Hot stab operation will result in fluid loss and salt water intrusion**
- **Isolation from ROV fluids is essential**
- **Volumes required to carry on the ROV**

Deepwater Challenges

Designing for subsea intervention is a challenge. As described previously, there are many areas that the successful developer and/or operator will keep in mind. In summary, the following must not be ignored.

- **Cost effective solutions**
- **Umbilical design**
- **System size and weight**
- **Standardization of subsea hardware**
- **Availability of equipment**
- **Trained personnel**
- **Manipulator durability/reliability**
- **Predicting component failures**
- **Autonomous vehicle delivery**



MAJOR SUBSYSTEM CONSIDERATIONS

As stated earlier in this chapter, the vehicle may be subdivided into functional subsystems such as the following:

- Structure
- Ballast/Buoyancy Control
- Propulsion
- Electric power
- Control and Navigation
- Viewing Systems
- Manipulators

The remainder of this section will discuss the above topics. The section following this (SELECTED SUBSYSTEMS – IN-DEPTH DISCUSSIONS) will provide additional material regarding design considerations for several of the subsystems.

Structure

The structure of a vehicle is generally divided into the frame and pressure resistant components, which are usually metallic and must be protected from corrosion.

Frame

The frame of a vehicle is the skeleton on which most components are mounted. In small vehicles, the buoyancy material may serve as the major structural element and there is no frame per se, however, frame construction in low cost vehicles has historically been plastic or aluminum. In the larger vehicles, including those that work at depths to 8,202 ft (2,500 m), aluminum has predominatly provided the strength and corrosion resistance required to date. Vehicle frames may be built in one of two methods:

- Free-flooding
- Closed or filled tubular

The advantages of the free-flooding frame are simplicity and repairability. The advantage of the closed or filled tubular frame is that the frame can provide buoyancy, but then it becomes a pressure vessel. The approach is generally the manufacturer's preference, however, free flooded frames are the most common design.

Material for frames may be 6061-T6 aluminum, stainless steel, titanium or GRP. Typically, aluminum is preferred for its corrosion resistance, ease of cutting and welding, and maintainability. Generally, the aluminum is either anodized or painted, and the color is usually black when in the vicinity of optical viewing systems. The black coating is used to reduce glare from lights, which in turn causes the auto iris in many cameras to stop down, thus making it difficult to see past the vehicle frame. Therefore, the coating is not provided primarily to protect the material; although it does help, anodes are used for this purpose.

High strength plastics or composite materials have been used to minimize surface finish or corrosion problems. However, these advantages must be weighed against the generally higher cost of using such advanced materials. These materials have several benefits that apply to areas such as mine countermeasures where the vehicle's magnetic signature plays a significant role.

Pressure Resistant Structures

Pressure resistant structures are used to house pressure sensitive equipment such as electronics and television cameras. Occasionally, they are also used for buoyancy. The principal characteristics desired in this material are:

- Availability
- High strength/weight ratio
- Corrosion resistance

There are many candidate materials and most of them have been used at one time or another. These include:

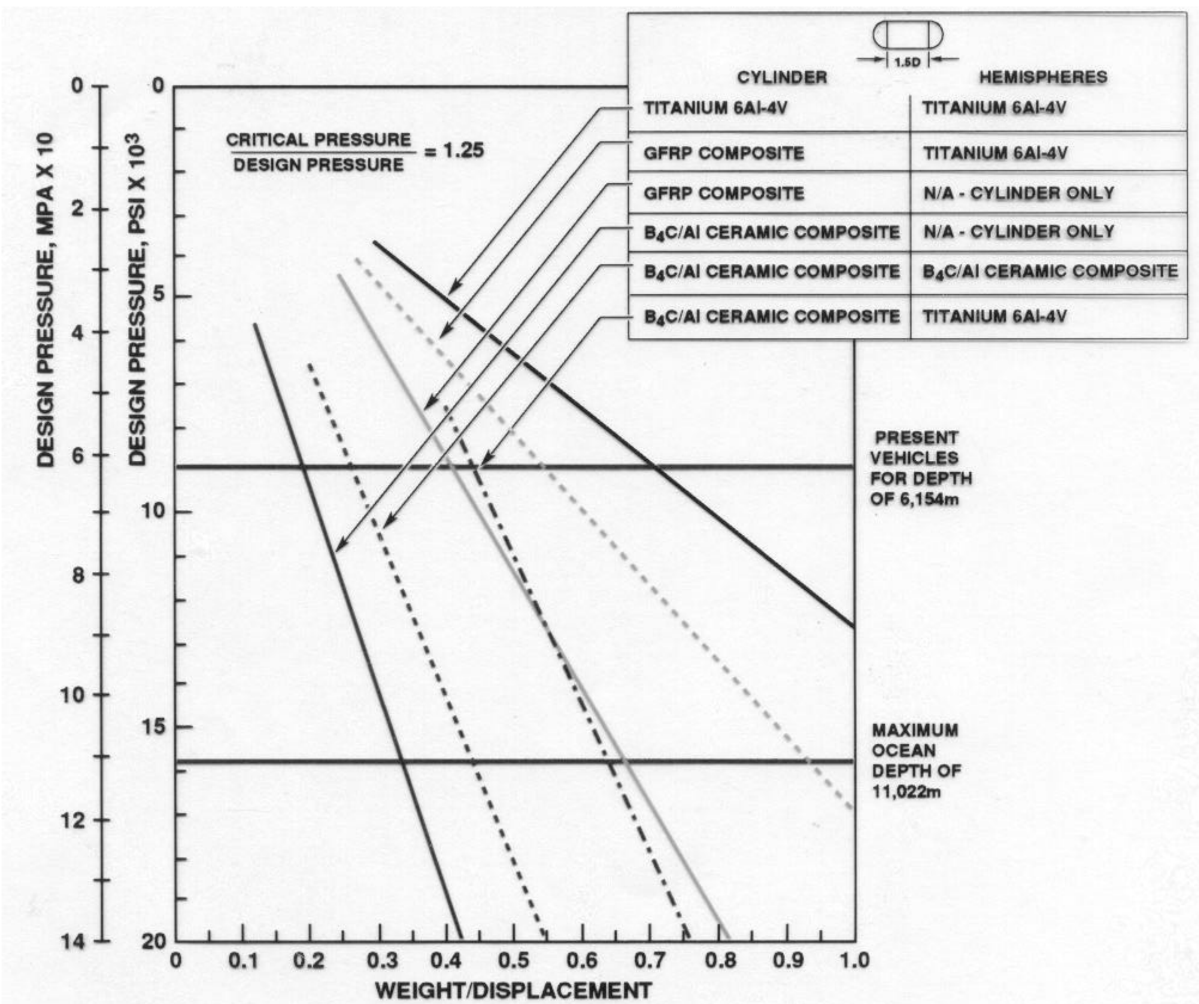
- Stainless Steel
- GRP (Glass Reinforced Plastic)
- Aluminum - 6061-T6 or 7000 series
- Titanium
- Ceramic

Glass Reinforced Plastic (GRP) is attractive, but is costly to fabricate in small quantity. It was used successfully on the Navy's AUSS vehicle, a 20,000-ft (6,096-m) search system. On some ROVs, 6061-T6 has been the most widely used material because of availability, light weight, strength and corrosion resistance.   Deep housings are often titanium, and more recently, the US Navy has made significant advances in the use of ceramics for deep ocean pressure housings. The figure on the following page provides a good comparison of the benefits of the various materials.

There are several points to consider when designing a pressure resistant structure; these are:

- Will the structure fail through yielding or buckling (i.e., will it be strength or geometry limited)

- Will the dimensions of the structure change sufficiently in the operating pressure range to damage the contents that are being protected



	Compressive Strength	Modulus of Elasticity	Density
B_4C/Al Ceramic Composite	400 Kpsi	45,000 Kpsi	0.09 lbs/in^3
Graphite Fiber Reinforced Plastic Composite	82 Kpsi	16,000 Kpsi	0.057 lbs/in^3
Titanium 6Al-4Va Alloy	120 Kpsi	16,500 Kpsi	0.160 lbs/in^3

Design curves for deep ocean pressure housings

Structures produced for ROVs were once designed using graphs and tables available in handbooks or guides, such as, Mark's Mechanical Engineer's Handbook, Principles of Naval Architecture, ABS or Lloyds Guidelines and textbooks on shell theory. However, with today's finite element analysis tools, even the most complex configurations can be accuratly designed and analyzed. The final designs are usually pressure tested for certification. In cases where it is desired to refine the design to produce a low weight solution, it is also conventional to test the prototype part to destruction.

Corrosion Protection

Zinc and magnesium anodes are used to provide structural protection. For the most part, zinc anodes are used on the frame and magnesium anodes on special items, such as manipulators and pan and tilts where parts may be electrically isolated by bushings.

Ballast/Buoyancy Control

Buoyancy and Stability

When designing an ROV, it is usual to attempt to use light weight components to keep the overall vehicle weight within practical limits, thus the reason for using aluminum and other light weight materials. The weight of the vehicle consists of:

- Subsystem components
- Lead margin/payload
- Buoyancy required to establish the desired operational specific gravity

It is conventional operating procedure to have vehicles positively buoyant when operating so they can be operated anywhere in the water column, and to ensure they will return to the surface if a power failure occurs. This positive buoyancy would be in the range of 5 lb (2.3 kg) for small vehicles and 11 to 15 lb (5.0 to 6.8 kg) for larger vehicles, and in some cases, vehicles will be as much as 50 lb (22.7 kg) positive. Another reason for this is to allow for near-bottom maneuvering without thrusting up, forcing water down, thus stirring up sediment. It also obviates the need for continual thrust reversal. Very large vehicles with air-blown ballast tanks that allow for subsurface buoyancy adjustments are an exception.

The measure of stability of a vehicle is conveyed by the assessment of the moment required to change the pitch angle of the vehicle. It is characterized by the equation:

$m = (W)\ BG \sin \Theta$, where:

m = moment = $(w)(d)$
w = weight of force where d = moment arm
W = vehicle weight
BG = distance between the center of buoyancy and center of gravity
Θ = pitch angle, or roll angle

Obviously, the selection of units must be consistent. That is, if "W" is in pounds and "BG" is in inches, "m" will have to be in inch-pounds. By inspection, it is clear that a large BG, which can be readily produced by having weight low and buoyancy high, produces an intrinsically stable vehicle. External forces do, however, act on the vehicle when it is in the water, which can produce apparent reductions in the BG. For example, the force of the vertical thruster when thrusting down appears to the vehicle as an added weight high on the vehicle and, in turn, makes the center of gravity appear to rise and hence destabilizes the vehicle in pitch and roll. The center of buoyancy and center of gravity can be calculated by taking moments about some arbitrarily selected point.

Most ROVs are designed to be as stable as practical (i.e., stiff in roll and pitch). When designing an ROV, stability may be kept high by placing heavy weight components such as electric motors low on the vehicle and buoyant components (GRP chambers and syntactic foam) high on the vehicle.

Ballast may be classified as fixed ballast or variable ballast (VB). Fixed ballast may be syntactic foam, closed chambers, and lead. Variable ballast may be provided by open, air-blown tanks called "soft tanks" or pumped or blown sealed tanks that can take full diving pressure called "hard tanks".

Fixed Ballast

Fixed ballast (positive fixed buoyancy) of a vehicle is achieved by pressure resistant buoyancy chambers, syntactic foam and lead to bring the vehicle to the desired specific gravity. Most vehicles use a syntactic foam block near the top of the vehicle to gain positive buoyancy. Syntactic foam will absorb small amounts of water over time-depth exposure. If a vehicle unexplainably loses buoyancy, the foam block should be suspect as some foams can be damaged by impact. Because some foams use a water barrier skin to prevent water absorption, impact damage should be repaired per manufacturers procedures as soon as practical.

There are currently two types of syntactic foam. One is a matrix of plastic macrospheres and glass microspheres in a binder, the other has microspheres only. In general, the micro/macro material is used for shallower water depth capability and microsphere material for greater depths. Obviously, the smaller the microsphere, the higher pressure it can take, thus the density of the foam increases as the depth of application increases. The trade off is based on cost, weight and pressure rating. Syntactic foam comes in many grades, distinguishable by its ability to withstand hydrostatic pressure. Essentially, the deeper the requirement, the more expensive the foam.

Vehicles that use sealed tubular frame members to gain buoyancy may be subject to operational damage. Therefore, it is conventional to use multiple compartments in the frames to prevent significant loss of buoyancy in the event of impact damage. Filling the frame with foam can also maintain buoyancy in the event of impact damage.

Depending on the depth requirement, it may be desirable to use a pressure vessel as buoyancy, however, this technique has found limited use in commercial ROVs. It is more common in AUVs where the primary structure is often a large pressure vessel.

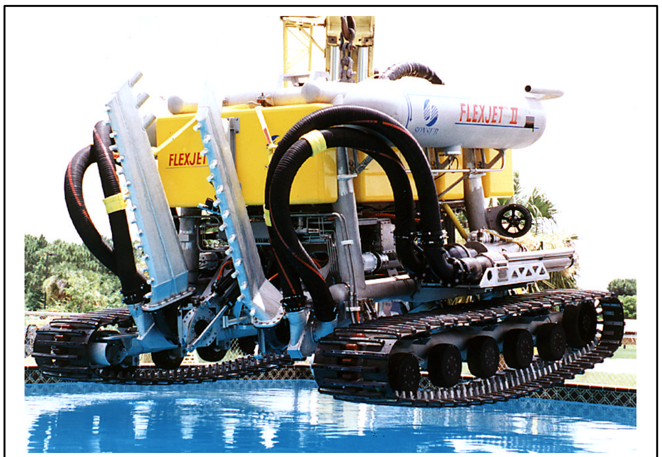
Fixed payload on the vehicle is usually in the form of several lead blocks. This lead may be exchanged for equipment without adjusting the vehicle's foam package.

Variable Ballast

Some vehicles are fitted with air-blown "soft" ballast tanks for lifting tasks. These tanks are usually located over the manipulator or lifting point. Variable ballast permits picking objects up from the sea floor and maneuvering them without thrusting downward. It also allows the ROV to be heavy when diving in high current situations. A typical soft ballast subsystem could include one or more 3000 psi scuba bottles, a pressure reduction regulator, a surface controlled solenoid valve, and a thin wall tank with a large opening at the bottom.

The soft tank approach has the disadvantage that air in the tank changes volume as the vehicle changes depth. The addition of pressure regulators referenced to ambient pressure vent valves in the top of the tank and water level controls will increase the soft ballast tank's performance, but make it much more complex. Variable payload may also be obtained by either using the vehicle's vertical thruster or by flooding or deballasting hard (i.e., pressure resistant) buoyancy chambers. Flooding a hard buoyancy chamber when a weight is released from a submerged vehicle is a simple, effective technique. Deballasting the hard chamber may be accomplished by forcing the water out with air when valves are opened or by pumping.

Variable buoyancy is uncommon in most ROVs but is widely used in hybrid vehicles where the vehicle must be neutrally buoyant for some operations and then become heavy for operations on the seafloor (e.g. cable and pipeline burial, repair, etc.). It is also used in applications where increased lift capability is required (e.g. salvage and recovery work). An example of this capability is Perry Tritech's *Flexjet* Trencher (right), which is a hybrid large ROV system and tracked vehicle. The trencher system weighs 26,460 lb (12,000 kg) in air, but in water can adjust buoyancy from 0 to 3,308 lb (0 to 1,500 kg) negative.



Perry's *Flexjet* Trencher showing VB tanks

The primary advantage of such a VB system is that the ROV can be flown to and positioned over the area while minimizing snap loading in the umbilical. It can then make itself heavy to counter trenching forces while operating its water jetters.

Communication and Control

Modern ROV systems have incorporated some of the latest technology in communications and control. With the fast moving PC-based computer technology available today, it has made sense for designers to switch to PC components for power, speed, reliability and availability around the world. Because of the speed at which such technology advances, this publication will not attempt to delve into the depths of vehicle electronics/control system design.

The use of fiber optics in modern systems provides excellent high bandwidth channels, giving the vehicle operator virtually all the information he needs, depending on the equipment installed on the vehicle. Incorporating fiber optics in the umbilicals is cost effective and results in smaller diameter cables, and with existing fiber optic slip ring technology, fiber optic telemetry systems are available for offshore and subsea use.

The topics of “fiber optics” and “cable design considerations” will be addressed in more detail in the “expanded discussions” section.

Propulsion

There are many considerations that must be taken into account when designing the propulsion system. Thrust, in most applications, is the largest factor relating to the power that will be required on board the vehicle. Most designers agree that high speed, servo-controlled thrusters are preferred due to the quick response and good control in tight situations.

General

Many factors are involved in the selection of a propulsion system. These include:

- Speed requirements
- Vehicle weight limitations
- Umbilical/tether size and length
- Acoustic and electrical noise limitations
- Auxiliary equipment (tools) required
- Available power
- Vehicle hydrodynamic drag

The speed a vehicle can attain is a function of the available power and the total drag imposed by the vehicle and tether. This is characterized by the equation:

$$\textbf{Drag} = {}^{1}/_{2} \times \sigma A V^{2}\ Cd$$

where:

σ = density of sea water/gravitational acceleration

density of seawater = 64 lb/ft^3 (1,025 kg/m^3)
gravitational acceleration = 32.2 ft/sec^2 (9.8 m/sec^2)

A = Characteristic area on which Cd is nondimensionalized. For vehicles, it is usually the cross sectional area of the front or the volume of the vehicle to the 2/3 power. For cables, it is the diameter of the cable in inches divided by 12 times the length perpendicular to the flow. For ships, it is the wetted surface.

V = Velocity in feet per second

(1 knot) = 1.689 feet/second
= 0.51 meters/second

Cd = Nondimensional drag coefficient. Cd is in the range of 0.8 to 1 based on the cross sectional area for most vehicles. Cd is in the range of 1.2 for unfaired cables, 0.5 to 0.6 for hair faired cables and 0.1 to 0.2 for faired cables.

NOTE: Calculations will be the same using metric units provided units are consistent. Do not mix meters and centimeters.

The power absorbed is characterized by;

$$\textbf{Power} = \frac{\textbf{Drag x V}}{\textbf{550}}$$

where 550 is a constant, which converts feet/pounds/seconds to horsepower. Thus, the power is proportional to the velocity cubed (recall that drag is proportional to velocity squared). Simply stated, because the power absorbed is proportional to the velocity cubed, a vehicle will require $(3/2)^3$ = 3.4 times as much power to go 3 knots as 2 knots. This means that if the power to weight ratio is constant, the propulsion system on a 3-knot vehicle will weigh 3.4 times that of a 2-knot vehicle. This does not turn out exactly this way because components come in discrete sizes. Nonetheless, it is clear that a requirement for higher speed has a dramatic impact on power, which in turn has the same sort of effect on system weight. A rule of thumb is that you can get about 35 to 40 lb (15.9 to 18.1 kg) of thrust per horsepower available.

The vehicle drag is only one part of the equation as the tether usually dominates the vehicle-tether combination. This can be best illustrated by an example for a vehicle cable system.

$$\textbf{Drag} = {}^{1}/_{2}\, \sigma\, A_v\, V^2\, Cd_v + {}^{1}/_{2}\, \sigma\, A_u\, V_u^2\, Cdu$$

(v = vehicle; u = umbilical)

As an example, suppose a vehicle is being live boated at 1 knot (1.9 km/hr) in 1,000 ft (305 m) of water. Suppose further that the cable is hanging straight down and there is a float on the surface and a weight on the bottom of the umbilical. Assume further that the umbilical drag from the ship to the float is small and the drag on the umbilical from the weight to the vehicle is small. Other data:

Umbilical diameter = 1 inch (2.54 cm)
The frontal projected area of the vehicle = 16 ft^2 (1.5 m^2)

Then:

Vehicle drag = 1/2 X 64/32.2 x 16 x (1.689)2 x 0.8
= 36 Ib (16.3 kg)

Umbilical drag= ${}^{1}/_{2}$ x 64/32.2 x (${}^{1}/_{12}$ x 1000) x $(1.689)^2$ x 1.2
= 284 Ib (129 kg)

This simple example shows why improvements in vehicle geometry do not make significant changes to system performance.

Propulsion Types

With this background, let us look at the types of propulsion systems. Propulsion systems are currently divided into two categories:

- Electro-hydraulic
- Electric

Electro-Hydraulic

Generally, the weight and relatively lower efficiency of an electro-hydraulic system effectively eliminates this system from consideration in vehicles weighing much less than 500 Ib (227 kg) In larger vehicles, however, it has the advantage of simplicity, ease of packaging, versatility, reliability, and low electrical noise. Although not a practical limitation in commercial operations, the higher acoustic noise inherent in the electro-hydraulic system may be important when considering the mission of the ROV, especially in the military mission of mine countermeasures.

Electric

Typical direct drive electric propulsion systems use a separate electric motor for each propellor, although a multiple output gearbox can be driven by a single motor.

Propulsion unit styles include:

- Continuous pitch propellors with constant speed motors (50/60 Hz)
- Variable frequency AC driven
- Universal motors with double reduction gear
- Brushless DC motors
- Permanent magnet brush type motors

Electrical propulsion has weight advantages in small ROVs. It is important when selecting propulsion strategy that the control requirements be considered simultaneously with motor selection since although some motors can be small, their motor controllers can have a significant effect on the overall package

Propulsion Control

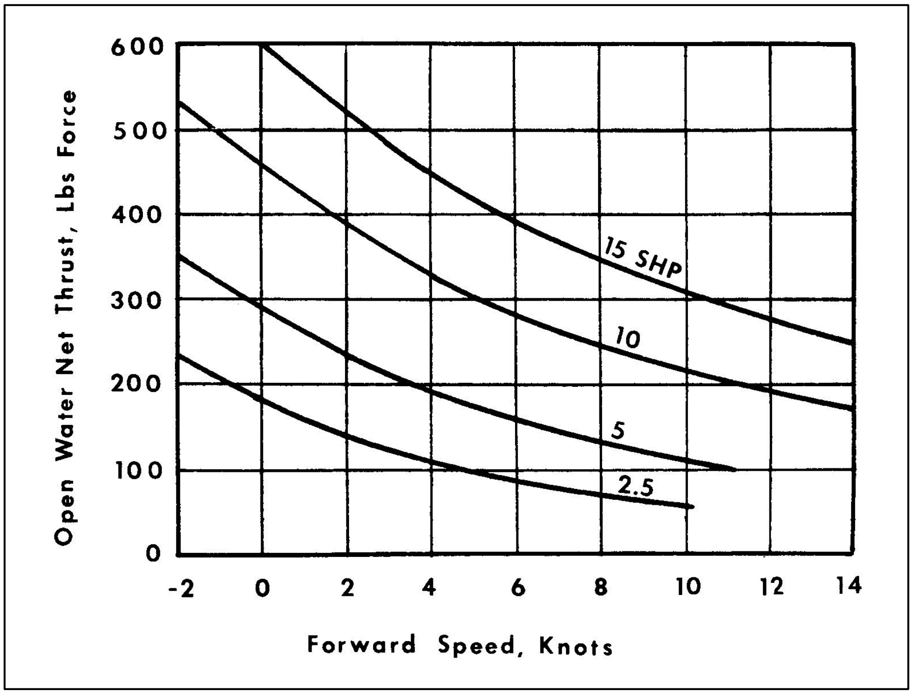
Electro-hydraulic systems normally have a constant rotational speed control motor driving a constant pressure hydraulic pump. The flow to the individual propellor/hydraulic motor is controlled by a servo-valve. Although the jetpipe type servo-valve is relatively immune to contaminated oil, system cleanliness is always important.

Direct drive electric motor propulsion systems may use controllable pitch propellors, variable frequency, variable voltage or pulsed voltage devices to control speed. Some of these control devices generate electrical noise that will affect video quality.

Standard Thrusters

The early days of inefficient thrusters are long gone, however, the inefficient engineer will always be on site. Therefore, a few words to the wise regarding thrusters are warranted. The ROV can be characterized as a small tugboat, with the consequence that the thrusters must be pitched to obtain good bollard pull–essentially the thruster's maximum static thrust. But one must be careful using bollard pull to determine thruster requirements. System efficiency must be taken into consideration along with the fact that most thruster output will decrease as velocity increases. The optimum pitch is also a function of vehicle speed. Therefore, the wise engineer will use the design curves available on the candidate thrusters to determine the proper size and location of thrusters based on expected vehicle speed. As an example of the effect of forward speed, the figure on the following page presents a graph of thrust vs. forward speed for an Innerspace thruster, Model 1002.

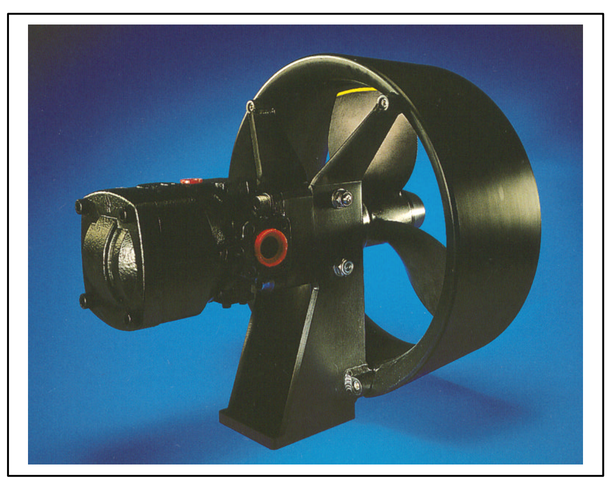
Thrust vs. speed



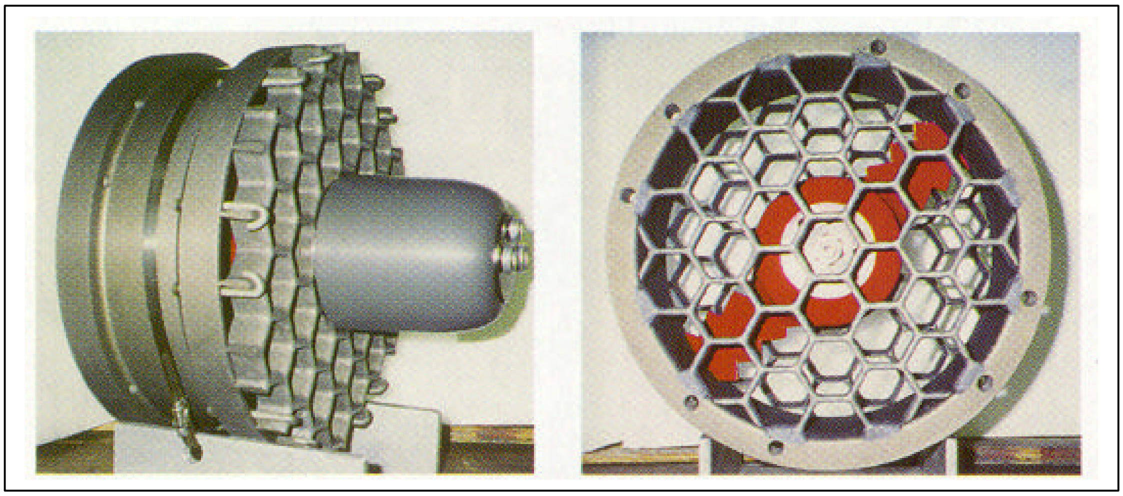
Since the velocity of the water surrounding the thruster, essentially the inlet velocity, effects the output of the thruster, the location of the thruster is very important. This becomes even more critical if the water is passing transverse to the thruster, which would be encountered with side or transverse thrusters when the vehicle is moving forward. An interesting effect is encountered when the thruster is located in the wake of the vehicle, where the water velocity is reduced; in this case the thruster will have a reduced inlet velocity and thus better thrust output. Accordingly, the location of the thruster in the vehicle frame or body is not just a matter of strapping on a thruster. Thruster size and location should be considered within the overall system, including the balance of power used by the thruster and other subsystems, ensuring that one doesn't rob the other of needed output in a critical situation.

Thrusters come in several sizes and configurations and may be powered electrically or hydraulically, through direct or gear drives, with or without shrouds or ducts. Generally, most thrusters will have a ducted shroud or a Kort nozzle to increase the output efficiency.

Hydrovision's *Curvetech* hydraulic thruster (right)



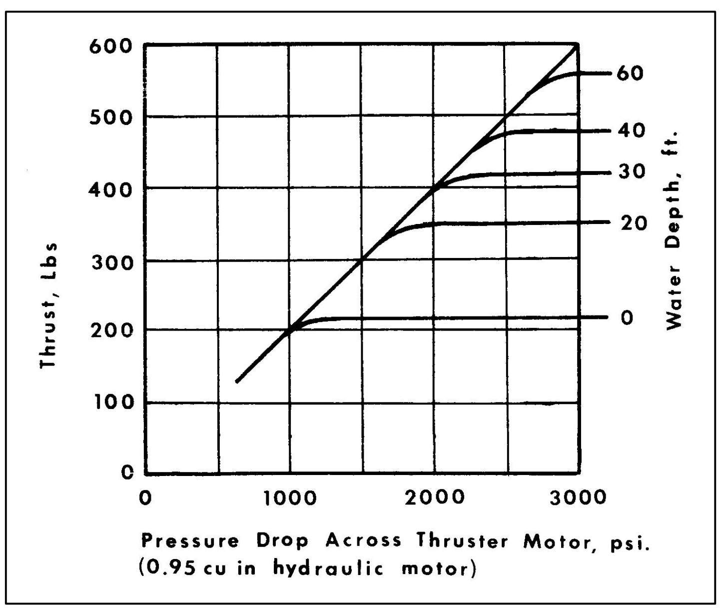
Most thrusters do not have the same thrust output in the forward and reverse directions due to interference from drive motors, mounting structures, etc. Also, protective covers can also effect the efficiency. However, with modern design and fabrication techniques, manufacturers are claiming excellent thrust characteristics in both directions, with and without protective covers. The test curves should be studied carefully and appropriate adjustments made as discussed earlier. As an example, Innerspace has developed a new thruster that uses a patented hexagonal directional screen. The thruster, which uses a new Orthoskew Propeller, is designed to increase thrust efficiency in both directions and reduce cavitation near the surface.



Innerspace high performance thruster

The fact that the previous thruster reduces cavitation near the surface brings up another design point. Increasing pressure reduces cavitation on the thruster, which is caused when a vapor cavity forms on the suction side of the propeller blade. This is caused when the absolute pressure at the blade falls below the vapor pressure of the water. Thrust loss due to cavitation as a function of depth is provided in the following figure for an Innerspace model 1002 thruster.

Effect of cavitation on thruster performance (right)



Another effect on thrust is water density. It can be shown that the thrust output is proportional to the cube root of the water density. Thus, for seawater with a specific gravity of 1.025, the thrust increase over fresh water is about 1 percent. Not a large amount, but the engineer optimizing thruster performance should be aware of every advantage, or if moving into fresh water–disadvantage.

Marketing brochures advertise output thrust ranging from 30 to 100 pounds per shaft horsepower input. Obviously, the results will be put in the best light for the company, so the thruster's design curves should be reviewed and appropriate adjustments made based on system integration. A rule of thumb that has been used for some time to estimate thrust or power requirements is 35 to 40 pounds of thrust per horsepower, however, it appears that technology is making the "modern thumb" a bit larger.

Unique Thrusters

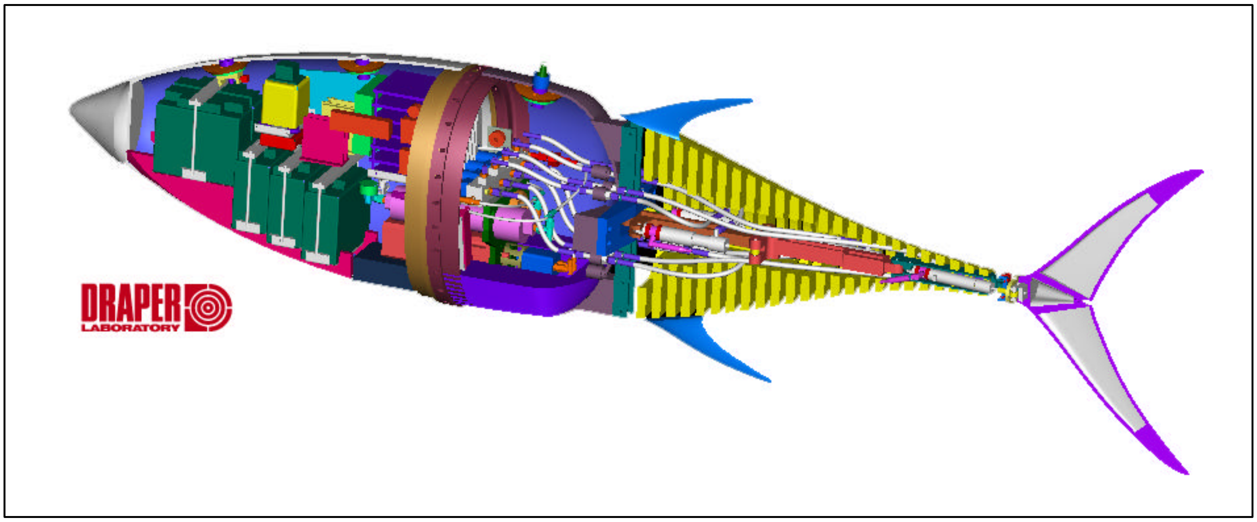
The previous section addressed the standard thrusters used on ROVs. This section will take a look at two new thruster techniques developed by Harbor Branch Oceanographic Institution (HBOI) and Draper Labs, respectively.

The unique thruster developed by HBOI is a solid-state electric ring propeller shown in the adjacent figure. The patented Electric Ring Propeller (ERP) uses a flux management technique developed by Fisher Electric Motor Technology, Inc. Contradicting standard design techniques, the ERP does not have a center propeller shaft. Instead, it uses a centerless propeller that is secured in a peripheral ring, which is held in a nozzle by water-lubricated ball thrust bearings.

With this approach, the ERP requires no propeller hub, shaft or lubrication and has no rotating seals. The bearings are the only moving parts, thus reducing maintenance. The rotor and stator are potted in epoxy and the fore and aft portions of the nozzle are made of syntactic foam material. The electronics, which provides variable speed, bidirectional control is located in a separate housing. The thruster design also lends itself nicely to "stacking," which allows counter-rotating pairs.

Electric Ring Propeller (right)

The second unique thruster design may not apply to work class ROVs, however, future AUV designers will certainly be interested in the research results of the Vorticity Control Unmanned Undersea Vehicle (VCUUV) at Charles Stark Draper Laboratory.



The Vorticity Control Unmanned Undersea Vehicle (VCUUV)

According to Dr Jamie Anderson of Draper Labs, in recent years, research in the propulsion and maneuvering mechanisms used by fish has demonstrated the utility of bio-propulsion for undersea vehicles. Despite advances in UUV technology, little progress has been made in improving propulsive efficiency and maneuverability. Most underwater vehicle designs employ a conventional propeller as the main propulsor and shrouded thrusters and/or control fins for maneuvering. Two types of vehicle designs are prevalent: torpedo shaped bodies streamlined for speed and range, or box-shaped bodies designed for maneuvering and station keeping. Unfortunately, most UUV missions require all of these capabilities: high transit speed, long range/duration, maneuverability and station keeping ability. Thus, fish are being considered as a potentially optimal UUV design in that they are able to cruise great distances at significant speed, maneuver in tight spaces and accelerate and decelerate quickly.

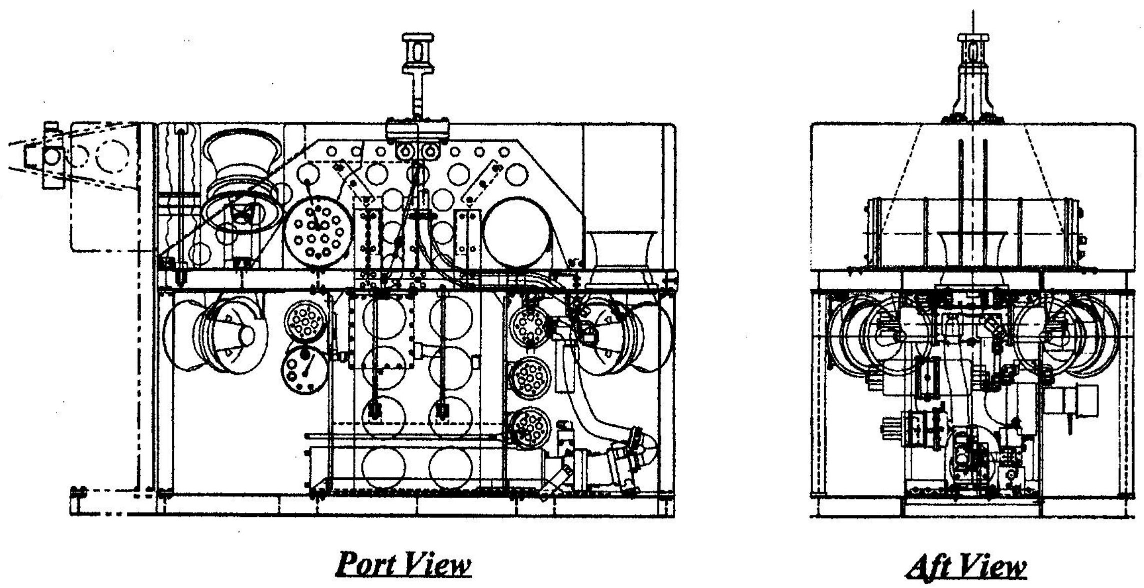
Because of this, Draper Laboratory is developing a flexible-hull UUV that propels and maneuvers like a tuna. Named after the vorticity control flow control mechanisms employed by fishes to propel and maneuver, the VCUUV mimics the form and kinematics of a yellowfin tuna. Across the broad spectrum of fish form and movement, tunas are most desirable as a vehicle platform since they are very streamlined, relatively rigid in the forebody and propel with low amplitude movements in conjunction with a high performance hydrofoil (caudal fin). The VCUUV prototype will function as a technology demonstration and research tool with which Draper will study the input/output relationships for steady swimming and fast maneuvering. Although many have begun work in the area of bio-mimetic propulsion, the VCUUV is the first autonomous fish-like vehicle that is appropriately sized for real world missions and payload.

Whether this unique method of propulsion finds its way into the field remains to be seen, but one fact is unavoidable–advanced robotic systems, many of them anthropomorphic or animal like in design are appearing at an ever increasing rate. And, they appear to be making their way from the research lab into the field in many instances.

Thruster Arrangement

The main differences seen from one system to the next are in arrangement and number of thrusters themselves.

It is common to find "vectored" thruster configurations on modern ROVs as they increase vehicle maneuverability. This approach can be seen is the drawing of the *Triton XL* below.



***Triton XL* thruster arrangement**

As can be seen from the drawing, all four horizontal thrusters are angled, enabling an equilateral thrust distribution for strong station-keeping capability in varying current conditions. The three vertical thrusters operate in a triad configuration providing pitch and roll control for work during unbalanced load conditions and vertical lift. Tilting the vertical thrusters also tends to clear the flow path of water through the thrusters, increasing efficiency.

Where high lift forces are required, up to four vertical thrusters may be incorporated. In some cases (usually smaller vehicles) only one vertical thruster is provided.

Control and Navigation

Control on an ROV can vary from a simple instrumentation package that sends heading and depth signals to the surface, to a sophisticated micro-computerized vehicle control system. The major subsystems of the control package on the ROV include: telemetry, performance monitoring, navigation control, and the operator video.

The telemetry package will normally vary to support the level of sophistication of the rest of the control package. Telemetry can be as simple as dedicated wires (in the umbilical) for each required function. This hardwire type system is simple to maintain but limited to the number of wires available in the umbilical. The next step in telemetry systems uses a multiplexer to take multiple signals and transmit them using a single pair of wires or a single coax. The two common methods of multiplexing (MUX) are to sample the signals one at a time and transmit their value at that moment, called time division multiplexing (TDM), or to modulate each signal onto radio frequency (RF) carrier signals at different frequencies, called frequency division multiplexing (FDM). FDM techniques consume large amounts of usually limited bandwidth on the signal paths in the ROV cables, but provide continuous signals without interruption. TDM methods can handle a large number of signals that do not require constant updating and transmit them over a relatively small band width. It is possible to combine both methods and optimize the use of limited signal pathways in the umbilical and tethers. The information/data handled by the MUX system can be either digital (typically a converted analog signal or a group of on/off command signals) or analog signals and transmitted in a variety of ways. Characteristics to look for in a MUX system include: line isolation to minimize or prevent damage when the umbilical or tether power and signal conductors short together; a method of fail-safing the controls in the ROV when the MUX fails (for whatever reason); graceful degradation designs that allow part of the MUX to continue to send correct data with other parts not operating; expansion capability (what does it take to add a channel); and repairability. With modern fiber optic cable systems, many of the bandwidth limitations that used to exist are slowly disappearing.

The performance monitoring system contains all the sensors needed to keep the operator aware of what's going on in the ROV. Information from such devices as leak detectors, propulsion performance or power output sensors, and similar input devices allow the operator to take the needed steps to either keep operating at reduced performance or abort the mission to protect equipment.

The navigation controls package contains all the sensors, controls and actuators needed to maintain the ROV in the desired position and attitude. The heading sensor is usually a true north seeking gyro, a directional gyro, or fluxgate compass to provide azimuth or heading information. The output of this sensor becomes the control input for the auto-heading circuit that controls the steerage thrusters. In general, magnetic compass is not useful at greater than 60 degrees north latitude.

A pressure sensor and/or altitude measuring sonar (altimeter) provide(s) the needed signals to automatically control either the depth of the ROV (seawater pressure) or height off the bottom.

Depending on design characteristics, the ROV may also have pitch and/or roll sensors to control the pitch and roll of the vehicle in establishing a stable ROV platform. Pitch and roll sensors are usually one of two types: pendulometer or vertical gyro. The pendulometer type becomes inaccurate when the ROV is accelerating in the X or Y direction, while the gyro suffers from a short life span. Additionally, when automatic position control in the X and Y directions is desired or required, a doppler sonar system can resolve both speed and displacement data needed to control thrust in the X and Y directions.

In addition to being used by the heading control loop, the azimuth signal is normally displayed on the surface console for the operator's information. The type of heading sensor used depends a great deal on the missions planned by the operator. The simplest sensor, the compass, becomes almost useless when working in or very near a large steel structure such as a platform, but is inexpensive and has an extensive lifetime. The gyro and gyrocompass both have finite life (specified by the manufacturer) before major overhauls are required. Gyros and gyro-compasses differ mainly in their accuracy with time and with respect to true north.

Similar to a diver operating with an umbilical, ROV operators must tend their umbilical or tether to prevent kinks, snarls, or twists, which may damage the cable. One circuit designed to assist the operator in this task is the turns or twist counter. The circuit counts the number of turns (360 degrees of rotation) the ROV accumulates, so that the operator can untwist the cable prior to recovery to ease the strain on the cable. On an operation where the surface vessel is live-boating (not moored or anchored), the ROV operator should be aware of the number of turns the ship accumulates so that those cable twists can also be taken out. Depending on the cable design, torsional twists can eventually cause damage to the cable if they are frequent enough.

The system console provides the interface between the work task, ROV, and operator(s).

The circuitry that provides the command signal may actually be located either in the surface controls or in the ROV depending on how the thrusters are controlled. If electric thrusters are used, and the speed control circuitry is located on the surface, then the ROV control circuitry would best be located on the surface. The sensors must still be located in the ROV requiring a MUX system that has the necessary speed, accuracy, and resolution to not interfere with the control action. If an electro-hydraulic system (or electric with constant speed motors) is used, the thruster controls would normally be located in the ROV to minimize the potential problems a loss of MUX signal could produce.

As more complex work tasks are attempted and controls to support them are developed for ROVs, the use of microcomputers in ROV systems will become dominant. The operator should be aware of several points when considering an ROV system. First is reliability. Electronic failures occur on ROVs just as they do anywhere else (when it will do the most damage). Systems using microcomputers may have only one processor doing all the work. This means that when it fails, the ROV loses all controls. A design based on use of discrete circuits has minimal components in common from one control circuit to the other, making it possible to have a single failure in one section of the controls with no impact on the other control circuits. With controls that have both a manual and automatic mode of operation, the loss of the automatic control of one mode would be of minimal impact to the operator; thus allowing the mission to be continued. This graceful degradation design philosophy must be weighed against the increased capabilities for fewer components in the microprocessor design.

The ROV’s viewing system has such a dramatic effect on the control and navigation of the vehicle, it will be addressed separately in the next section.

Viewing Systems

The main TV cameras should have the capability to move–rotate (pan) and pitch (tilt) to aim the lens in the desired direction. The operator’s cameras should have a full field of view in the direction of travel to avoid hitting obstacles, in addition to a full view of the working area (including the manipulators' area of reach). Additionally, the TV cameras should have overlapping fields of view where possible to allow cameras to operate as backups systems. The ability to view behind the ROV to watch the umbilical or tether cable for fouling or snags, and to inspect the ROV itself (to check for damage or problems) is desirable. The pan and tilt assemblies that perform this work are generally either electrically or hydraulically powered. The electric units are self-contained requiring only the electric drive commands to operate while the hydraulic units require an external hydraulic power source (usually available from the propulsion power source) and the electric command (to actuate the valves). The hydraulic units can generally handle much more equipment than the electric units can, and can be operated in a servo slaved mode for faster aiming or automatic controls.

Aiming the camera requires that you know where the camera is pointing. The best method of showing the pan and tilt information is to overlay it on the TV screen with the actual picture so that the viewer does not have to look away from the picture.

An important part of navigating an ROV is seeing where the vehicle is going. TV cameras have problems similar to human vision–a lack of sensitivity at low light levels. Unless a stereo camera system is used, depth perception is non-existent. Therefore, a dual perspective camera system is almost mandatory for any complex work tasks. Poor water clarity also obscures the ROV's TV.

TV camera lighting for subsea applications requires adaptability to allow the end user to vary the position and intensity of the lights to best illuminate the work area for each mission. Since both color inspection cameras and black and white low light sensitive cameras are likely to be used, the best lights to use contain no hot spots (areas of the light pattern that are brighter than others) and are color balanced (see section on Underwater Viewing Systems). The availability of spare bulbs and their life expectancy should also be considered in lighting selection.

Thankfully, many of the larger, modern ROV systems have the capability of carrying as many as 10 TV cameras while operating 5 or more simultaneously due to the emergence of fiber optic technology. With the advent of components such as the Focal Technologies fiber optic video and data multiplexer, up to eight uncompressed video channels and 15 bi-directional data channels may be transmitted on one single mode optical fiber. ROV umbilicals may carry up to 12 fibers, of which several are designated as spares in case of breakage.

With the ability to carry many more cameras, many vehicles have both stationary and movable, pan and tilt type camera arrangements. A typical pan and tilt system is shown in the following figure. The Remote Ocean Systems pan and tilt unit is an all electric system that uses brushless 120 VAC motors and precision gear reducers to drive the equipment.

Remote Ocean Systems pan and tilt system

Manipulators

The front end of the vehicle is almost always the "business end," which is well demonstrated in the following figure. It is fitted with manipulators for performing work, and TV cameras, lights and sonars so operators can see to navigate and conduct the work operations assigned.

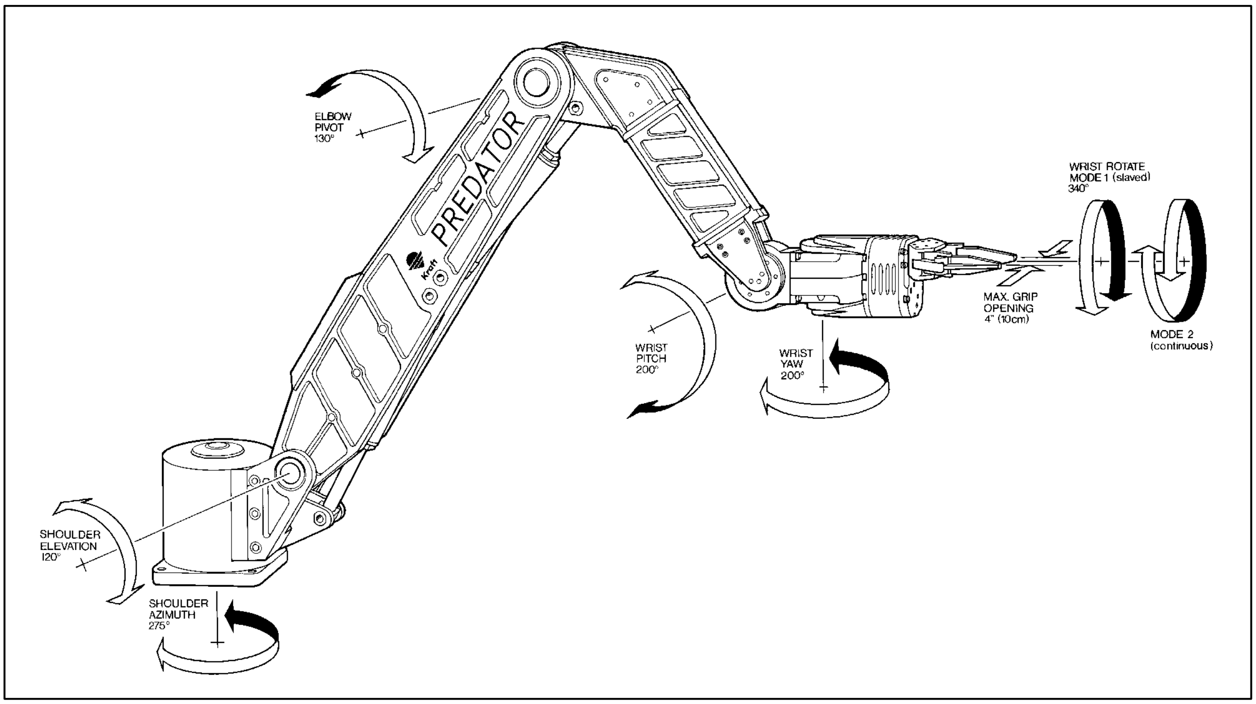
The business end of a *Triton XL* 250 ROV

The operator can have the best manipulator system ever developed, however, if he can't see it, he can't use it. TV cameras and lights, usually mounted on "pan & tilt" devices (electric or hydraulic), enabling the vision systems to be moved, increase the operator's viewing envelope and thus his ability to perform useful work.

The choice and integration of a manipulator system is complex, and the vehicle designer should consider the following:

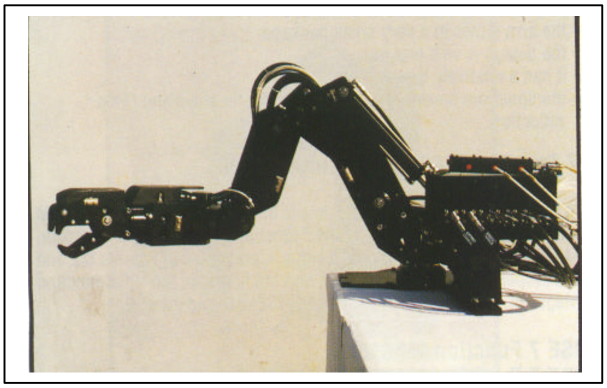
- Number installed
- Rate controlled
- Spatially correspondent
- Force feedback
- Lift
- Reach

An example of the degrees of freedom provided by an advanced manipulator is shown in the following figure of a Kraft TeleRobotics Predator arm.

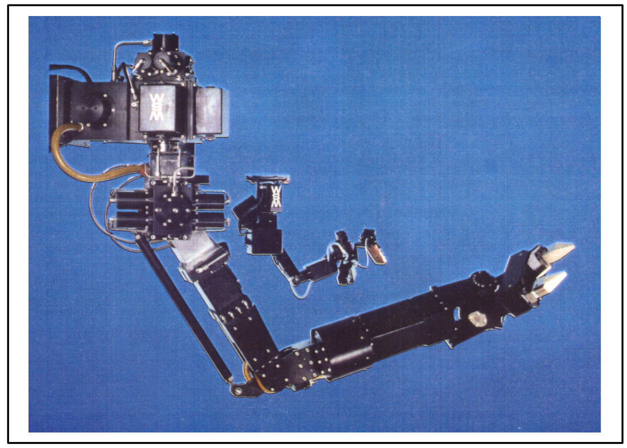


***Predator* 7-function manipulator operational envelope diagram (Kraft TeleRobotics Inc.)**

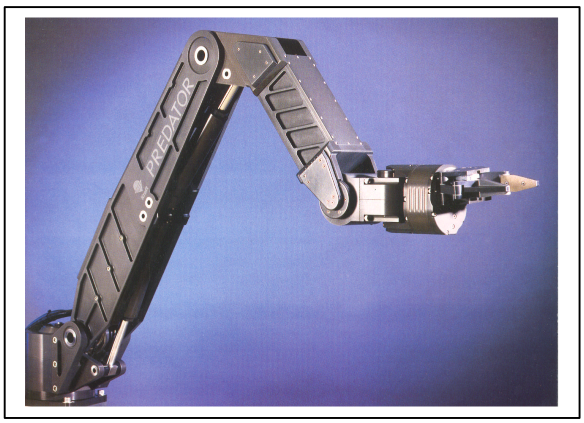
Manipulator designs have improved dramatically over the years, integrating effective ergonomics along with power, dexterity and control. They have become easier to operate and maintain and have incorporated space-age technologies that have increased their reliability. Various configurations, degrees of freedom, and end uses are available as exhibited in the following photos of many of the manipulators that are on the market today.



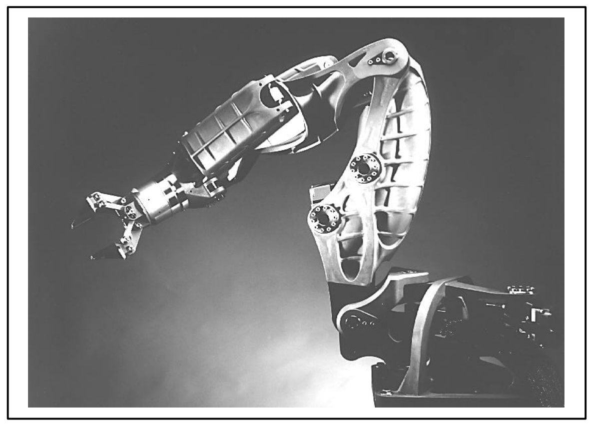
ISE's 7-Function *Magnum*



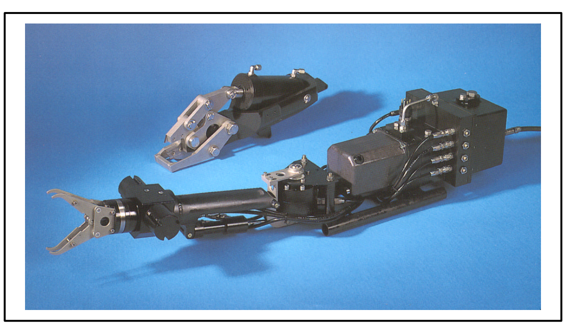
***THE ARM* by Western Space and Marine**



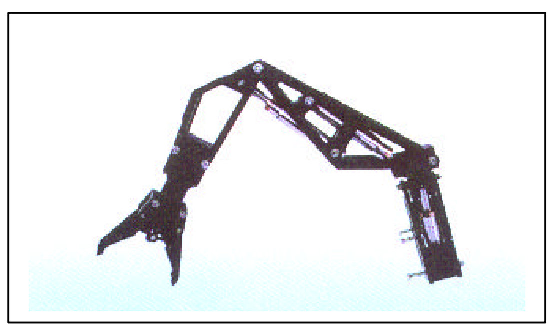
Kraft TeleRobotic's *Predator*



Schilling's *Conan* Manipulator



HYDROVISION's Mini Manipulator



Tritech's EH5 Electro-Hydraulic Arm

One of the leading manipulator developers, Schilling Robotics of Alstom Automation, provides a detailed discussion of manipulator requirements in the Manipulator section later in this chapter.

Schilling's *Orion* 7-function manipulator

ROV Cable Design Considerations

Introduction

Most ROVs require a cable to transfer the mechanical loads, power, and communications to and from the vehicle. Alternatives to this would be vehicles under autonomous or semi-autonomous control (such as an acoustic link), or vehicles with expendable cables such as fiber optic microcables. For now, we are concerned with the standard ROV, which uses an electro-mechanical cable. There are two general categories for ROV cable:

- Umbilical cable:
  - Ship to the ROV or Tether Management System (TMS)
- Tether cable:
  - TMS to the ROV.

Initial cable design considerations include:

- **Power requirements**
- **Signal requirements**
- **Strength requirements**

The power and signal requirements are usually the most important considerations because the cable's main purpose is usually to transmit power to the ROV and return signals from it. However, the strength is also an important consideration. Therefore, as discussed earlier, when designing an ROV system, you usually have to look at all the parameters in parallel when designing a cable.

Power Requirements

The power requirements translate into amperes. For each ampere it is necessary to have enough material to conduct the power to the far end. Most conductors have resistance to electrical energy flow. This creates a voltage drop, and it is necessary to keep this value as small as possible to provide power to the source. Therefore, it is necessary to use material with as low a resistance as possible.

The most common material for providing power through a cable is copper. The most common form for electrical cable conductors is electrolytic tough pitch (ETP) copper with no coating, or bare-copper. Coatings are available for special purposes, but most increase the resistance to electrical current, so bare-copper is the most common material for ROV cables.

Another consideration is insulation on the conductors to contain the electrical energy. There are two general insulation families:

- Thermoplastic, a material that repeatedly softens or melts when heated and hardens when cooled. Some examples are:

  - Polyethylene (PE)
  - Polypropylene (PP)
  - Polyvinyl Chloride (PVC)
  - Polyurethane (PUR)
  - Nylon
  - Fluorocarbons (TEFZEL™ & TEFLON™)

- Thermoset, a material that does not soften on heating. Some examples are:

    - Cross-Linked PE (XLPE)
    - Chlorosulfonated PE (Hypalon™)
    - Chlorinated Rubber (Neoprene™)
    - Ethylene Propylene Rubber (EPR)
    - Ethylene Propylene Diene Rubber (EPDM)
    - Styrene Butadiene Rubber (SBR)

ROV cables usually use thermoplastic materials. They process easier than thermoset materials and thermoplastics cover a broad range. Thermoset materials require special processing equipment. However, because thermoplastics soften or melt with heat, it is important to know both the operating environment and the current requirements. The cable designer needs to look at all these parameters in choosing the proper material.

The operating voltage is another consideration in the cable design. It is important to limit voltage stress on the insulation. If this is too high it can cause the insulation to fail and the electrical energy to exit the conductor before it reaches its objective, which can create a hazardous condition. Therefore, it is important for the cable design to address the insulation voltage stress. Also, a separate conductor for an emergency ground is common as a safeguard in case there is a breakdown in the insulation.

Signal Requirements

The signal requirements translate to attenuation losses. The signal, whether electrical or optical, attenuates through both the conductor and the insulator. This loss varies with both the signal transmission media and frequency.

Signal transmission can be either analog or digital, and either electrical or optical. The system usually dictates the signal transmission type, and this is beyond the cable design scope. However, it is important for the cable designers to understand the media and as many parameters about the signal transmission as possible so they can select the proper conductor for the signals.

Copper conductors with thermoplastic insulation are also common for electrical signals, similar to power conductors. Signal transmission wires frequently require a shield from electro-magnetic interference (EMI) and radio-frequency interference (RFI). Also, it is common to group the signal transmission wires separate from the power conductors.

There are both balanced and unbalanced electrical transmission schemes, and the system determines this requirement. Typical balanced lines are twisted-pairs, and unbalanced lines are coaxial.

Other parameters to consider for signal transmission include:

- Impedance
- Capacitance
- Frequency

You can also transmit signals over optical fibers. Fiber optics come in various types:

- Multi-Mode
    - 50/125
    - 62.5/125
- Single-Mode
    - Dispersion-Shifted
    - Non-Dispersion-Shifted

The system requirements determine the optical fiber type. Some parameters to consider in any type fiber optic are:

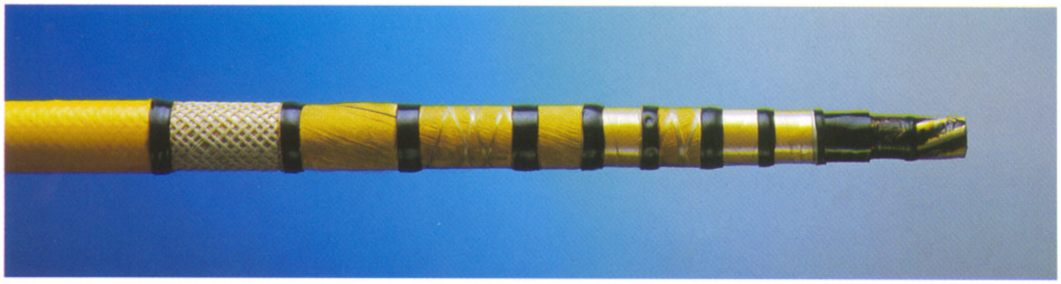
- Attenuation
- Bandwidth
- Wavelength

There are different ways to package the fiber optics in a cable:

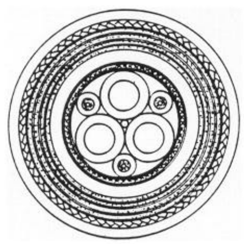
- Loose-tube buffer
- Tight-buffer

The optical fibers can have either an individual buffer on each fiber optic, or they can have a common housing for all the optical fibers. The user will need to weigh the trade-off with the different approaches for his application because there is no single design that is correct for all applications.

Several standard cable design specification sheets follow throughout this section and are representative of state-of-the-art cables provided to the offshore industry by South Bay Cable. A pioneer in the ROV cable industry, they have been designing, manufacturing, and testing such cables for over 40 years.



E-O-M UMBILICAL
(Electro-Optical-Mechanical)



SB-37535

POWER CONDUCTORS 3 KVAC-3 UNITS
AWG No. 4(STRANDED)B/C

RUGGEDIZED FIBER OPTICS-3 UNITS
SINGLE MODE, 200 KPSI PROOF
.55 dB/KM (MAX) @ 1300 nm
KEVLAR-TPE BUFFER

INTERSTICES WATERBLOCKED

OVERALL SHIELD
BARE COPPER BRAID

POLYURETHANE INNER JACKET

STRENGTH MEMBER
MULTI-LAYER SERVED KEVLAR

OUTER JACKET
REINFORCED POLYURETHANE

CABLE CHARACTERISTICS	ENGLISH	METRIC
PHYSICAL		
OUTER DIAMETER	1.360 INCHES	34.54 mm
WEIGHT IN AIR	1,124 LBS/1000 FT	1,673 KG/KM
WEIGHT IN SEA WATER	479 LBS/1000 FT	713 KG/KM
MECHANICAL		
BREAKING STRENGTH	80,000 LBF	178 KN
MAXIMUM LOAD	14,300 LBF	64 KN
MIN. BEND DIAMETER	40 INCHES	1 METER
ELONGATION @ 14,300 LBF	0.5% NOMINAL	0.5% NOMINAL

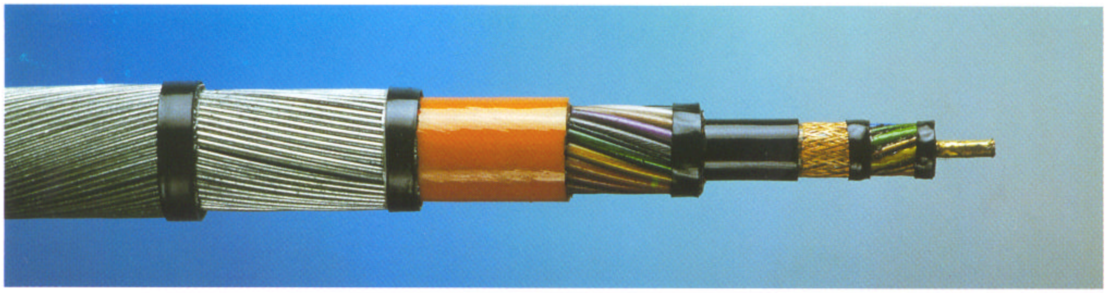
Strength Requirements

The strength-member provides the mechanical link to the ROV. It usually has to support the cable weight, the ROV and any additional payload, and handle any dynamic-loads. Also, the cable size can influence the load on the cable due to drag. Therefore, there are many variables to consider when choosing the cable strength.

Steel is the most common strength-member material for umbilical cables. This material is usually a carbon steel wire with a galvanizing coating on the outside to protect the steel from corrosion. This material's tensile strength, modulus, and abrasion-resistance protect the cable from damage in service.

Synthetic fibers, such as KEVLAR™ from DuPont, can reduce weight. Synthetic fibers are frequently necessary in tether cables, and also in umbilical cables for deep-water systems. Synthetic fiber strength-members usually require an overall jacket for abrasion resistance. A synthetic strength-member is generally more expensive than steel, but the weight difference can be significant. In many cases this is the only way to get to the necessary depth.

There are reasons to consider both strength-member materials for different applications; these issues should be discussed with your cable manufacturer.



ROV UMBILICAL STEEL

SB-36670

SHIELDED QUADS-4 UNITS
AWG No. 20(STRANDED)B/C

COAXIAL RG-59 TYPE-3 UNITS
AWG No. 22(STRANDED)B/C

SINGLE CONDUCTORS-6 UNITS
AWG No. 18(STRANDED)B/C

POWER CONDUCTORS-17 UNITS
AWG No. 11(STRANDED)B/C

INTERSTICES WATERBLOCKED

JACKET
POLYURETHANE

ARMOR-STEEL WIRES
TWO LAYERS GIPS

CABLE CHARACTERISTICS	ENGLISH	METRIC
PHYSICAL		
OUTER DIAMETER	1.680 INCHES	42.67 mm
WEIGHT IN AIR	3,330 LBS/1000 FT	4,956 KG/KM
WEIGHT IN SEA WATER	2,440 LBS/1000 FT	3,631 KG/KM
MECHANICAL		
BREAKING STRENGTH	100,000 LBF	444 KN
MAXIMUM LOAD	25,000 LBF	111 KN
MIN. BEND DIAMETER	36 INCHES	91.4 cm
ELECTRICAL (DC RESISTANCE @ 20° C)		
RG-59 CENTER CONDUCTOR	16.4 OHMS/1000 FT	53.8 OHMS/KM
RG-59 BRAIDED CONDUCTOR	4.8 OHMS/1000 FT	15.7 OHMS/KM
SHIELDED QUAD CONDUCTOR	10.4 OHMS/1000 FT	34.1 OHMS/KM
SHIELDED QUAD SHIELD	4.3 OHMS/1000 FT	14.1 OHMS/KM
AWG No. 18 (1 KV) CONDUCTOR	6.2 OHMS/1000 FT	20.3 OHMS/KM
AWG No. 11 (3 KV) CONDUCTOR	1.6 OHMS/1000 FT	5.2 OHMS/KM
SHIELD OVER INNER LAYER	2.0 OHMS/1000 FT	6.6 OHMS/KM

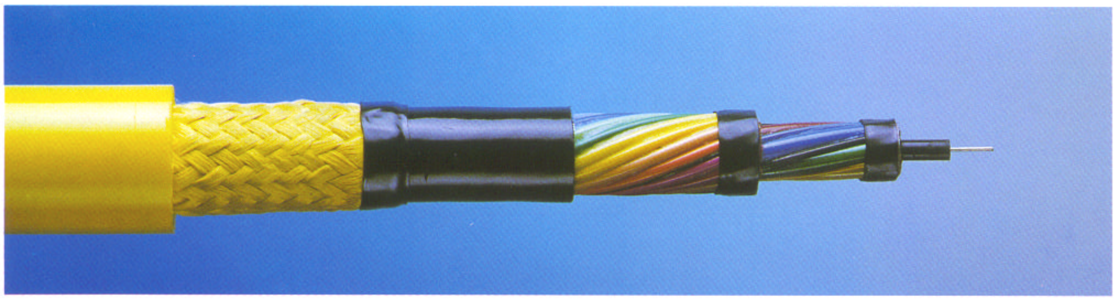
Conclusion

A cable for an ROV is a special component because it is the primary link to the vehicle, providing power, signal, and handling strength. Thus, it is necessary to consider all these features when designing an ROV cable.

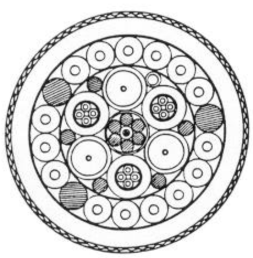
The vehicle size, weight and operating depth, as well as the vehicle motors, subsystems, and payload, all combine to determine the cable design, which is usually unique to the vehicle.

These brief descriptions of cable design considerations are just a starting point. Because each ROV has unique requirements, abilities, and limits, it is important to discuss your unique cable requirements with someone who has experience in this area.

South Bay Cable



ROV TETHER
LARGE VEHICLE



SB-39063

75 OHM COAX-3 UNITS
AWG No. 22(STRANDED)B/C

SHIELDED QUADS-3 UNITS
AWG No. 22(STRANDED)B/C

FIBER OPTICS
3 MM FIBER OPTICS IN A SS TUBE

DRAIN WIRE

POWER CONDUCTORS-15 UNITS
AWG No. 18(STRANDED)B/C

INNER JACKET
POLYETHYLENE

STRENGTH MEMBER
KEVLAR BRAID

OUTER JACKET
THERMOPLASTIC ELASTOMER

CABLE CHARACTERISTICS	ENGLISH	METRIC
PHYSICAL		
OUTER DIAMETER	1.78 INCHES	45.2 mm
WEIGHT IN AIR	1,133 LBS/1000 FT	1686 KG/KM
WEIGHT IN SEA WATER	27 LBS/1000 FT	40 KG/KM
MECHANICAL		
BREAKING STRENGTH	14,000 LBF	62 KN
MAXIMUM LOAD	2,000 LBF	9 KN
MIN. BEND DIAMETER	20 INCHES	508 mm

Acoustic Positioning/Measuring Systems

This section will address the following:

- Types of Acoustic Positioning Systems
- Some important Acoustic Theory
- Why do we design things this way?
- Case Study - Dynamically Positioned Drilling

However, prior to discussing these topics, the following background information is provided:

Some Abbreviations

CIF	Common Interrogation Frequency
COMPATT	Computing and Telemetering Transponder
dB	Decibel
EHF	Extra High Frequency
GPS	Global Positioning System
HF	High Frequency
Hz	Hertz, measure of frequency (cycles per second)
LBL	Long Baseline
LF	Low Frequency
LOP	Line of Position
MF	Medium Frequency
PAN	Programmable Acoustic Navigator
ms	millisecond
SBL	Short Baseline
SL	Signal/Source Level
SNR	Signal to Noise Ratio
SPL	Sound Pressure Level
SSBL	Super Short Baseline
SVP	Sound Velocity Profile
TL	Transmission Loss
USBL	Ultra Short Baseline
VHF	Very High Frequency
Vp	Speed of Sound in Water

Some Terminology;

- **Beacon**
  Transponder, Pinger, Responder, COMPATT, Tilt Beacon
- **Transceiver**
  Hydrophone, Transducer, Dunker, RovNav
- **Frequency Band**
  Low, Medium and Extra High frequency (LF, MF and EHF)
- **Buzz words (often used as excuses for system failure)**
  Thermoclines, ray bending, velocity profiles, multipath
- **Noise**
  Ambient noise, self noise, reverberation, machinery noise, flow noise, structure noise

Some Definitions;

Pinger (free running) - A device that constantly emits pings at a preset repetition rate. Some pingers can be switched off via a mechanical switch; others can be acoustically switched off. Older USBL and SBL systems usually worked with free running “Pingers”.

Responder - A device that is hard wired to the surface and emits a ping after it is electrically triggered. Usually used on ROV’s. Allows for positioning of noisy remote devices as no interrogation signal is required.

Transponder - A stand-alone device that responds to acoustic interrogation. Various types of transponders are available from many manufacturers. Intelligent transponders, which usually have other sensors attached, have microprocessors within them and can communicate to the surface equipment via acoustic telemetry.

Acoustic transducer - Usually a ceramic device, which is encased within a waterproof housing, that turns electrical signals into acoustic signals and vice-versa. Some “transducers” will include matching analog hardware and pre-amplification circuitry within the same package.

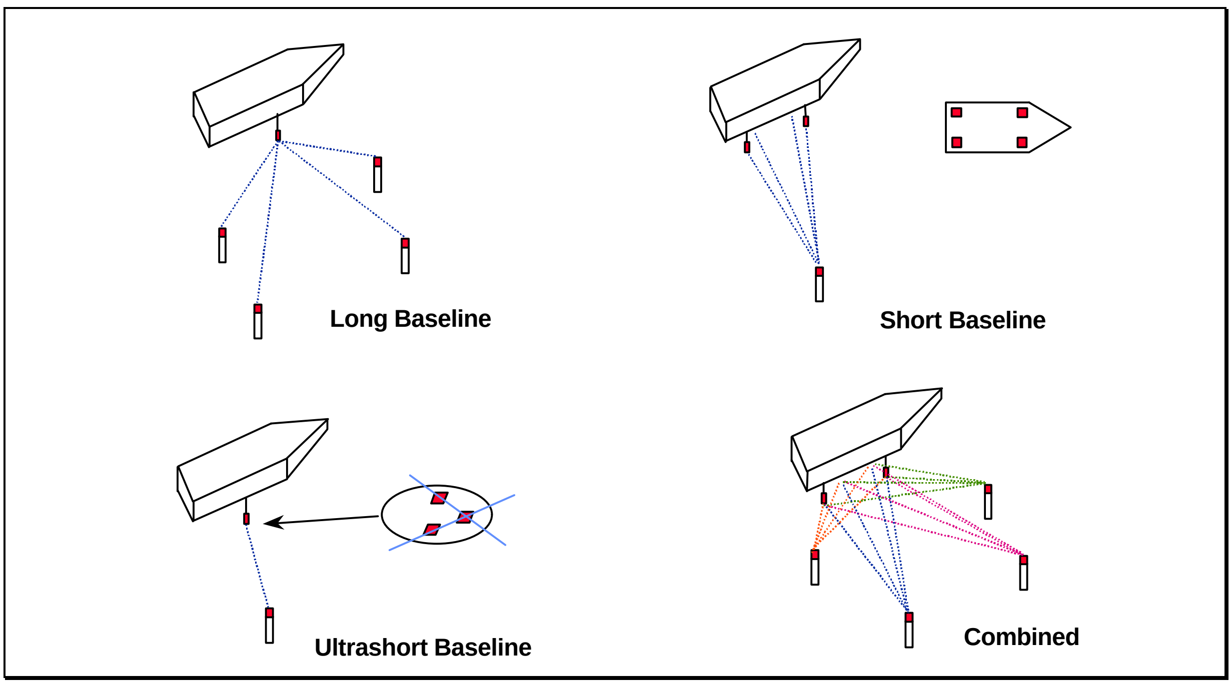
Hydrophone - A device, similar to a transducer, which receives acoustic signals and turns them into electrical signals. A Hydrophone does not transmit acoustic signals.

Acoustic Transceiver - A device that has both analog and digital electronics for the generation of acoustic signals. “Transceivers” also usually have range measurement/telemetry capability within the unit. Transceivers usually only require a communication channel and power to a central processor. A Transceiver communicates digitally rather than via analog signals.

Speed of Sound in water (Vp - Sound Velocity) - This is the speed at which sound travels in water. The main elements that affect Vp are temperature, pressure (depth) and salinity. The factor with the greatest impact is temperature. In salt water Vp is around 4,921 ft/sec (1,500 m/sec). For acoustic positioning operations Vp must regularly be monitored with the appropriate sensors, such as CTDs.

Types of Acoustic Positioning Systems

The following figure shows the four types of acoustic positioning systems that will be discussed in this section.



Ultra Short or Super Short Baseline

This system measures a range and bearing from the surface mounted transceiver (Hydrophone) to a beacon mounted on the seafloor. A USBL system can work in pinger mode or transponder mode. The position measured from a USBL system is measured with respect to the vessel and as such a USBL system needs a Vertical Reference Unit (VRU) and (possibly) a gyro to provide a position that is seafloor (earth) referenced.

Long Baseline

A long baseline system measures a position with a “range-range” technique. That is, a LBL system measures ranges to transponders that are at known points on the seafloor. As the system measures these ranges from known points it can then work out where the surface transducer is with respect to this seafloor “array or grid” of transponders.

The position measured by a LBL system is seafloor referenced. As such, a LBL system does not require a VRU or gyro.

Short Baseline

A short baseline system measures a range and bearing from the surface mounted hydrophones or transceivers to a beacon mounted on the seafloor.

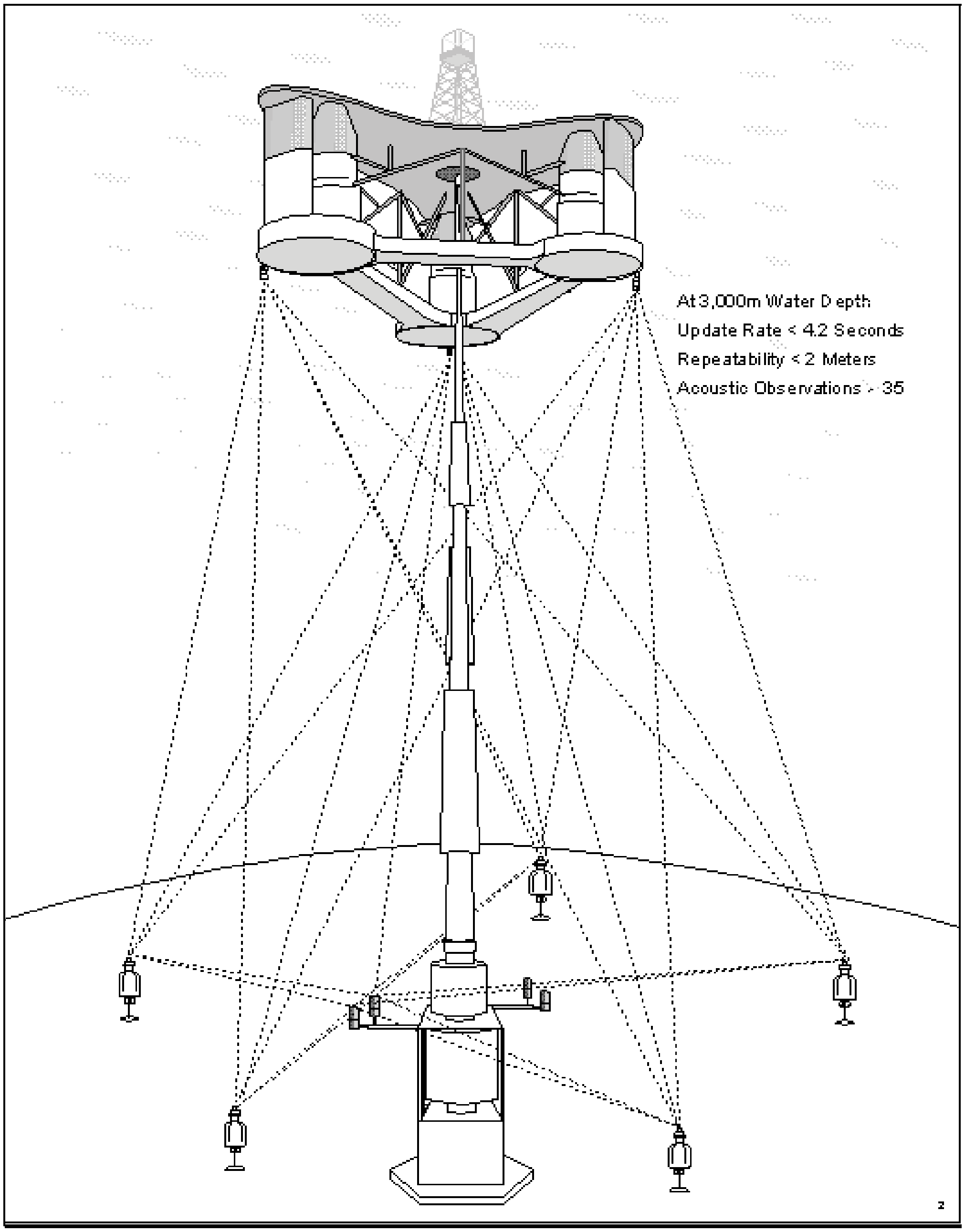
An SBL system can work in pinger mode or transponder mode. The position measured from an SBL system is measured with respect to the vessel and as such a USBL system needs a VRU and (possibly) a gyro to provide a position that is seafloor (earth) referenced.

Combined Systems

Combined systems get their name because they combine the benefits from all of the above systems and provide a very reliable, redundant position reference system for DP operations. Combined systems come in many varieties:

- Long and Ultra Short Baseline (L/USBL)
- Long and Short Baseline (L/SBL)
- Short and Ultra Short Baseline (S/USBL)
- Long, Short and Ultra Short Baseline L/S/USBL

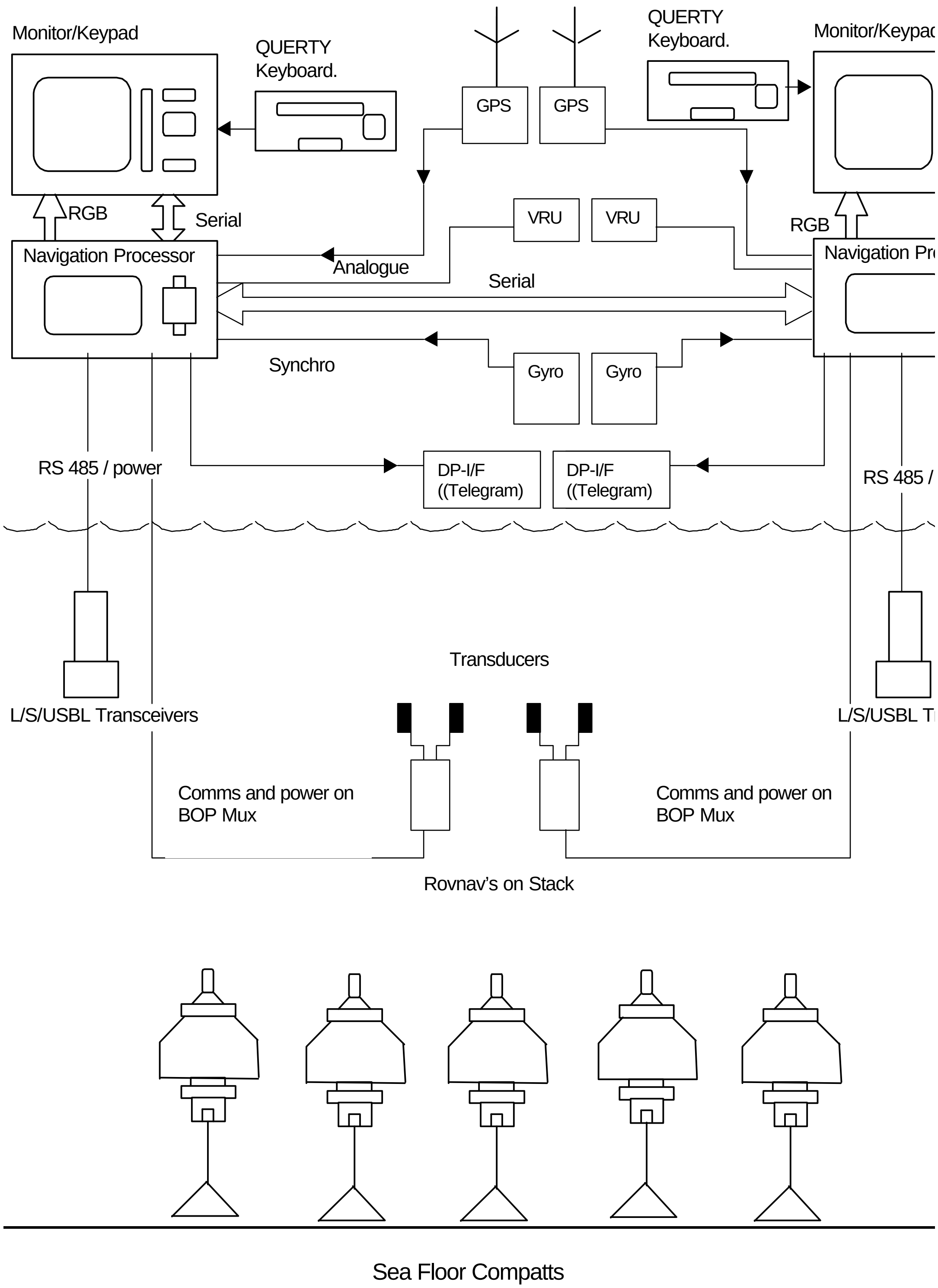
The following two figures provide examples of such combined systems:



The complete solution: Long/Short/USBL

SYSTEM BLOCK DIAGRAM

Integrated LUSBL System Block Diagram



Advantages/Disadvantages of Positioning Systems

Ultra Short Baseline (USBL)

- Advantages

  - Low complexity
  - Easy to use
  - Good range accuracy
  - Ship based system

- Disadvantages

  - Detailed calibration of transducer required–usually not performed accurately
  - Position accuracy depends on ship's gyro and vertical reference unit
  - Minimal redundancy
  - Large transducer/gate valve requiring accurate/repeatable orientation

Short Baseline (SBL)

- Advantages

  - Good range accuracy
  - High update rate in pinger mode
  - Redundancy
  - Ship based system
  - Small transducers/gate valves
  - No orientation requirement on deployment poles

- Disadvantages

  - Positioning accuracy depends on water depth due to need for vertical reference unit.
  - Very good dry dock/structure calibration required

Long Baseline (LBL)

- Advantages

  - Very good position accuracy independent of water depth
  - Redundancy
  - Wide area of coverage
  - Single, simple deployment pole

Long Baseline (LBL) (Con't)

- Disadvantages

  - Complex systems requiring more competent operators
  - Large arrays required
  - Longer deployment/recovery time
  - Calibration time required at each location

Integrated systems can provide the best of both worlds

- Convenience
- Speed
- Accuracy

Long and Ultra Short Baseline	(L/USBL)
Long and Short Baseline	(L/SBL)
Short and Ultra Short Baseline	(S/USBL)
Long, Short and Ultra Short Baseline	(L/S/USBL)

Important (Basic) Acoustic Theory

A discussion of some basic acoustic theory is warranted. The following areas will be discussed:

- Optimum frequency Bands

- Transmission loss

  - Divergence Loss - Spreading
  - Transmission Loss Anomaly - Attenuation

    - Absorption - Compression/rarefaction (work)
    - Scattering - particles and bubbles

  - Boundary Loss - Bounce
  - Refraction loss - bending (distortion)

- Noise

  - Ambient
  - Self noise

The following will not be discussed, however, these items should also be reviewed for a more complete understanding of basic acoustics. References are provided at the end of this section:

- Range resolution
- Frequency, bandwidth, pulse width, source level
- Detection, validation - hard limiting
- Uncertainty in speed of sound in water

Optimum Frequency Bands

What frequency band equipment to use in what water depth?

	Frequency	Max Range	Typical LBL Accuracy
Low Frequency (LF)	**7.5 - 15kHz**	**10 - 12Km**	**2.5-5m**
Medium Freq. (MF)	**18 - 36kHz**	**2.5 - 3.5Km**	**0.25-1m**
Extra High Freq.. (EHF)	**50 - 110kHz**	**<1Km**	**<0.05m**

Please note that the accuracy's shown above are for static sampled positions. For dynamic un-sampled but filtered positions a consideration for update rate and motion has to be made. This could decrease the estimated accuracy by a factor of two.

Usually, the selection of the frequency band is related to the required accuracy. The only real consideration of water depth comes when we cannot "talk" to the equipment from the surface. If we look at the above maximum ranges, the equivalent depths will be:

- LF OK to full ocean depth
- MF Problems beyond 11,483 ft (3,500 m)
- EHF Problems beyond 2,625 to 3,281 ft (800 to 1,000 m)
- VHF Problems beyond 328 ft (100 m)

Even at the above depths, in the case of the MF equipment, some special transducers may be required to work between the seafloor and the surface if the vessel is very noisy. Also, the pressure rating (mechanical design) of the housing and transducer may not be for the required depth. In some instances, a piece of equipment may be mechanically rated to a depth, but will not acoustically work to that depth.

Take, as an example, a 8,202 ft (2,500 m) rated omnidirectional COMPATT in the MF band. Should this equipment be deployed in 8,202 ft (2,500 m) of water under a very noisy DP vessel, with the source remaining at the surface, then the acoustic signal transmitted from the seabed is probably not strong enough to be detected by the surface equipment.

If the accuracy of the system is required, but it looks as though it cannot reach the surface, then the interrogator has to be taken to depth. An example of this in the construction sector is the methodology for jumper measurements at the Mensa site, where EHF equipment will be used at a 6,562 ft (2,000 m) depth with the interrogators on the ROVs. This will only work if relative accuracy is required.

Acoustic positioning systems are available in all of the above frequency bands.

- The majority of full ocean depth systems are in the LF band.
- The majority of LBL and USBL systems used for dynamic positioning, construction/installation work offshore are in the medium frequency band.
- Jumper measurements (metrology) usually use EHF equipment.

The Sonar Equation

The performance of any acoustic system can be predicted using a sonar equation that expresses the relationships between received signal and surrounding in-band noise. If an example results in a negative signal to noise ratio (or less than 5 dB) then most acoustic positioning systems will fail to detect the incoming signal (see figure on following page).

Signal to Noise ratio (dB) = (E - N),

where E = (SL - TL)
N = 20 log10 (NT),

and NT = @ (NA2 + NS2 + NR2),

where E = Received Signal Sound Pressure in dB re 1 microPascal
N = Total Received "in-band" Noise Sound Pressure level in dB re 1 microPascal
SL = Source level in dB re 1 microPascal at 1 m
TL = One-way Transmission Loss in dB
NT = Total Noise Pressure Level in microPascals
NA = Ambient Noise Pressure Level in microPascals
NS = Self Noise Pressure Level in microPascals
NR = Reverberation Pressure level in microPascals.

The source level (SL) is the acoustic power, measured in decibels, transmitted into the water by the equipment.

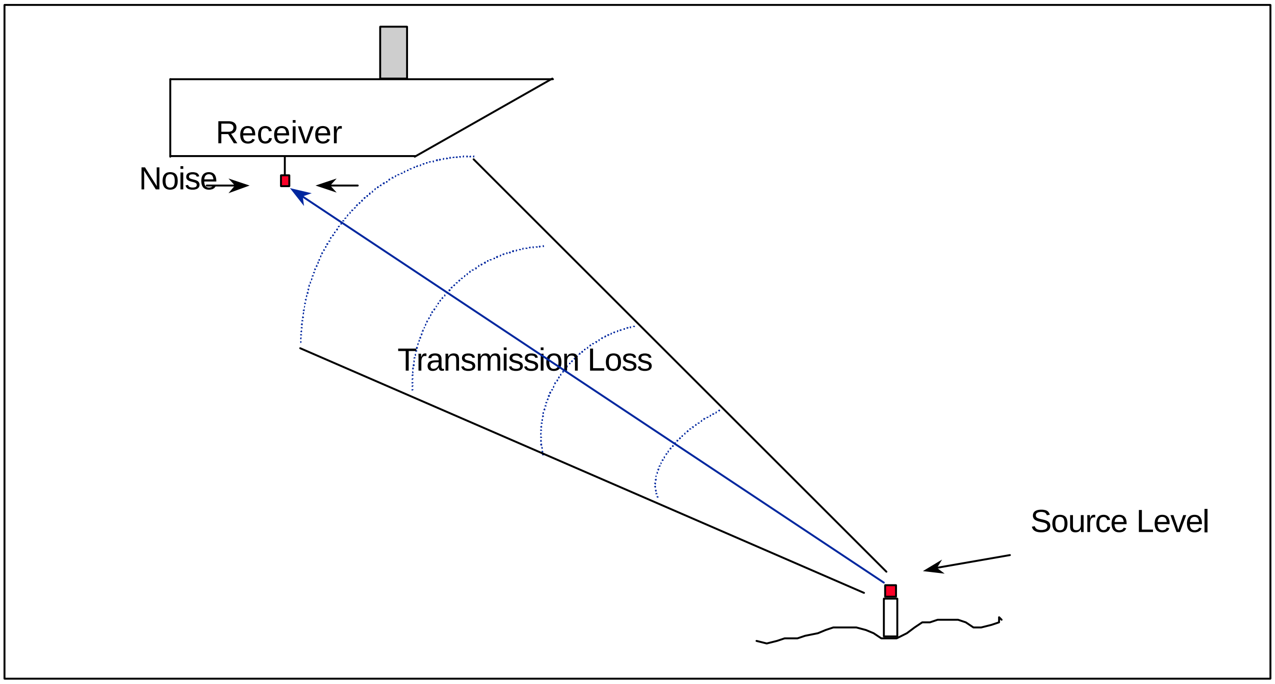


Figure relating to the Sonar Equation

Transmission Loss

"Transmission Loss" is the amount of energy lost as an acoustic signal travels through the water column. The total transmission loss is the sum of the spreading loss and the attenuation loss. Together, the spreading and attenuation may be expressed as:

TL = 20 log10 R+ @ R,

where TL = one-way transmission loss in dB,
R = range in meters,
@ = attenuation coefficient in dB per kilometer.

Typical values for the attenuation coefficient, at a temperature of 24 degrees centigrade over the frequency band used for acoustic positioning, are:

Frequency (kHz)	10	30	50	70	90
@ (dB/km)	1	7	15	22	30

The transmission loss (TL) of the signal, as an acoustic pulse travels through the water, is caused by divergence loss (spreading), transmission loss anomaly (attenuation), boundary loss (bounce) and refraction loss (bending). These are described as follows:

Spreading

The spreading loss is a geometrical effect caused by the energy of the acoustic pulse spreading out as the wave front expands. In homogeneous deep water, power is radiated equally in all directions and spherical spreading occurs. Energy loss from this increases as the square of the distance (6 dB per doubling of range) and is normally used to estimate the maximum range of an acoustic positioning system, unless specific information dictates otherwise. The loss is expressed by the logarithmic relationship:

Spreading loss = 20 log10 R,

where R = the range in meters.

Attenuation

As well as the purely geometric dilution of the signal strength due to spreading, losses are also caused by absorption and scattering of the sound energy as it propagates through the water.

- Absorption

Absorption obeys a different law of variation with range than the loss due to spreading. It involves a process of conversion of acoustic energy into heat and thereby represents a true loss of acoustic energy to the medium in which propagation is taking place. It is a complex function of frequency, temperature, pressure and salinity.

- Scattering

Although scattering is a component in the attenuation of sound energy, its contribution is less important than that of absorption. When acoustic pulses strike reflectors, such as bubbles, fish and suspended matter, they are deflected and small amounts of sound energy are scattered in many directions. The part of the scattered ray returned to the receiver is known as reverberation. Multipath reverberation associated with surface vessels and sub-surface structures is important in positioning applications.

The following table provides examples of total transmission loss versus frequency.

Total Transmission Loss versus Frequency

Frequency kHz	10	20	30	40	50	60	70	80	90	200
Range meters										
10	20	20	20	20	20	20	20	20	20	21
30	30	30	30	30	30	30	31	31	31	32
100	40	40	41	41	42	42	42	43	43	46
300	50	50	52	53	54	55	57	58	59	67
1,000	61	63	67	70	75	78	82	85	90	115
3,000	73	79	91	100	115	124	136	145	160	-
10,000	90	110	150	180	-	-	-	-	-	-
15,000	90	129	189	-	-	-	-	-	-	-

Received Signal Level

Successful acoustic position monitoring is ultimately determined by the ability to detect, with minimal timing jitter, the interrogation and reply signals. This in turn depends on the signal to noise ratio (SNR) at the seabed transponders and at the interrogators.

As a general rule, transponders deployed on the sea floor will be in a quieter acoustic environment than the interrogating units at the surface or on an ROV. Therefore, operational performance calculations for acoustic positioning systems normally refer to the interrogator at the surface. The acoustic signal level received back from a seabed beacon, assuming no masking, reverberation or ray bending, is the device's source level (SL) less the transmission loss (TL).

Signals will be detected with a wide band SNR down to +5 dB with most equipment available on the market, although +8 dB through +15 dB is normally used as a safety margin to give a high probability of detection (say 95 percent) and a low probability of false alarm. Some of the "Correlation/Chirp" based systems may improve on this. With a noise background of +100 dB in the frequency band and SNR of 5 dB, the maximum detectable range at the mid frequency of each band, for a source of 193 dB is:

Frequency Band	**Maximum Detection Range**
LF	10 km (6.2 mi)
MF	3 km (1.9 mi)
HF	1.5 km (0.9 mi)
EHF	800 m (2,625 ft)
VHF	100 m (328 ft)

Increasing the transponder source level by 6 dB to 199 dB ref 1 uPa at 1 meter increases the maximum detectable range to 9.3 miles (15 km) at LF, or more important, allows an acoustic positioning system to be used up to a range of 6.2 miles (10 km) with an increased noise background. Unfortunately, the increased source level will cause the penalty of a shorter operational life.

Noise Considerations

Noise is usually the biggest problem encountered when using acoustic positioning systems–this is a critical area when it comes to successful operations and should not be ignored. Lessons learned can be very expensive.

The basic signal processing technique used in most acoustic positioning systems utilizes a wide-band filter, hard-limiting amplifier and narrow-band filters, followed by the detectors and decision-making circuits and software. The narrower the narrow-band is, the more channels that can be squeezed in, but larger pulse lengths are required, which reduces transponder lifetime. The range timing resolution of a system under low noise conditions is ultimately limited by the rise time of the narrow band filter. Noise causes increased jitter, because it affects detection of the envelope and will eventually prevent the reception of an interrogation or reply signal. There are five main classifications of acoustic noise:

- Ambient noise
- Self noise - (acoustic pollution)
  - Propulsion noise
  - Machinery Noise
- Flow noise
- Reverberation noise
- Structure noise

These noise sources vary in their characteristics and will be discussed in the following sections:

Ambient Noise (NA)

Ambient noise is generated by external factors such as waves, wind, rain, general traffic, sea life, etc.

Generally these levels are low; in the 10 to 100 kHz band they are less than 40 dB above 1 uPa in a 1 Hz bandwidth. However, heavy rain can increase the noise level by 15 to 25 dB at 10 kHz.

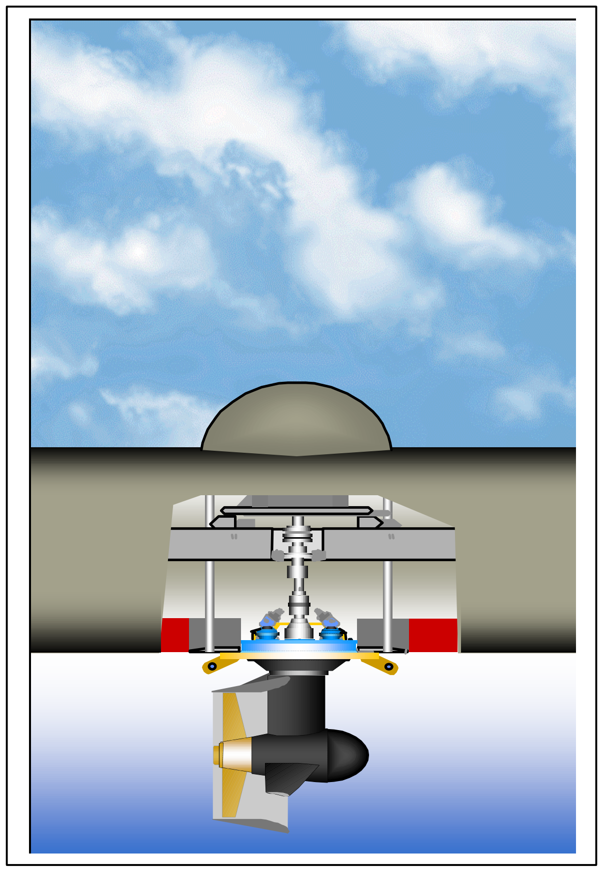
The noise level in shallow water for a given sea state is about 9 dB above the deep water case. This can increase by approximately 25 dB in typical offshore oil field environments.

Self Noise (NS)

Self noise includes noise that is entirely generated as part of the acoustic position monitoring operation and includes propulsion, machinery, hydrodynamic (flow), circuit noise.

- Propulsion Noise

Propulsion noise is principally cavitation noise caused by the tip vortex stream and blade surface cavitation of a thruster or vessel/ROV's propeller. Variable pitch propellers are generally more noisy than fixed pitch propellers. In some variable pitch instances, minimal thruster load will be far noisier than a fully loaded thruster. The noise spectrum level normally increases with frequency to peak between 100 to 1000 Hz and then decreases at about 6 dB/octave. Fixed pitch thruster noise levels usually increase with speed. In all cases it is very important to position transceivers as far away from thrusters as practically possible.



The acoustic noise associated with drilling operations on deep-water drill ships has been measured at 150 dB re 1 microPascal across the frequency band. Thus, for a hull transducer mounted 66 ft (20 m) from the main noise source, with a directivity of 15 dB between the signals returning from the seabed transponders and the noise from the rig thrusters, the effective wide band self noise level at the transducer is:

$$NS = 150 - [20 \log 10 (60/3) - 15] = 109 \text{ dB}$$

If a minimum wide band signal to noise detection threshold of 5 dB is assumed, it can be shown that under these conditions the maximum positioning range, with a standard MF beacon will just exceed 1.2 miles (2 km).

- Machinery Noise

Machinery noise is associated with generators, winches, etc. on the surface vessel, or with the hydraulic system on ROVs. It is difficult to quantify this noise source as it depends on how the different systems are installed and operated. Experience has shown that acoustic noise associated with the hydraulic system on ROVs (pumps, pressure release valves, etc.) is frequently the limiting factor in the performance of acoustic positioning systems. In some instances it can completely interrupt operations.

As an example, noise data from a *Hydra* ROV noise study is discussed below. This test was to confirm actual noise levels and to establish their effect on range measurement jitter using equipment operating in the MF band. The noise level in the same horizontal plane as the hydraulic pumps at a distance of 6.6 ft (2 m) was typically in excess of 140 dB ref. 1 microPascal. This was higher than expected and severely limits the LBL range capability. It was related to the hydraulic power pack and bypass relief valve, with the level decreasing when the thrusters were running. The syntactic buoyancy material on the *Hydra* attenuated the high noise level (in excess of 20 dB), and successful acoustic range measurements were shown to be possible with an omnidirectional transducer raised up on an extension ram above the syntactic foam. At a depth of 9,843 ft (3,000 m), syntactic foam becomes acoustically transparent.

Flow Noise

Flow noise is created by any turbulent boundary layer. Generally, unless excitation and radiation of sound occurs from structures within the surface vessel, this is not a major noise source. However, it can critically affect towed transducers with poor hydrodynamic characteristics, therefore, most acoustic manufacturers now offer some form of hydrodynamic towed body, which permits LBL operations at survey speeds up to 6 to 8 knots (11 to 15 km/hr).

Reverberation Noise (NR)

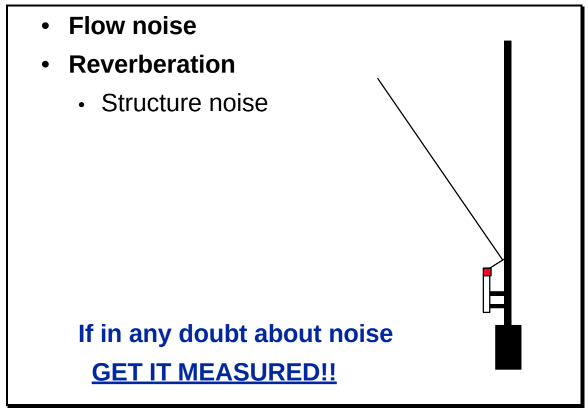
Reverberation noise arises as a direct consequence of an acoustic positioning system operation and can be subdivided into four major classifications:

- Volume reverberation - Scattering by particle matter, both animate and inanimate
- Sea surface reverberation - scattering off the surface
- Sea bottom reverberation - scattering off bottom layers
- Structure reverberation - scattering off man-made structures

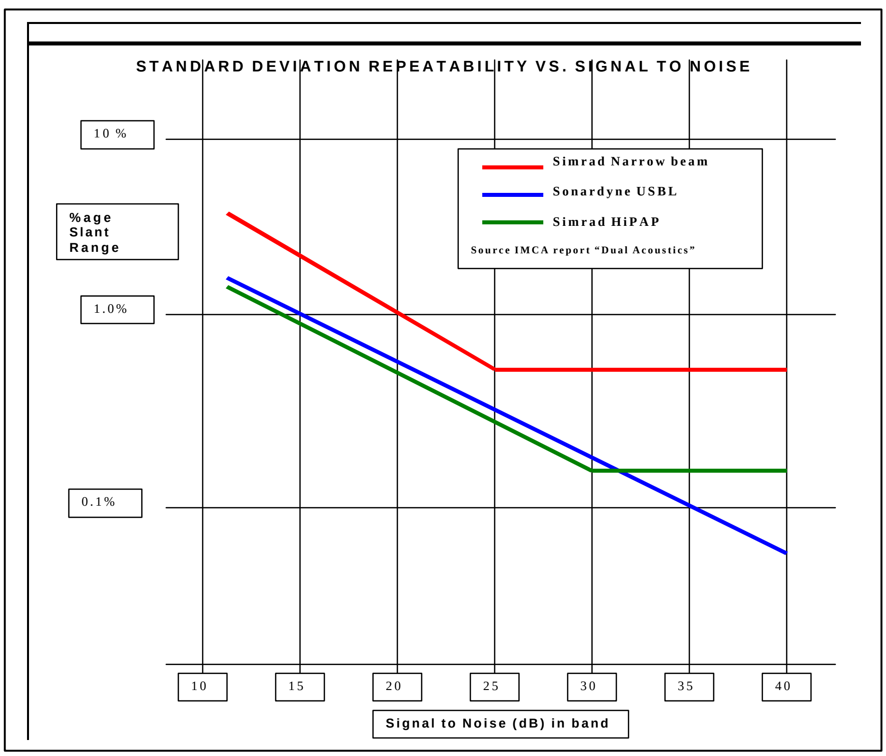
The latter three types are the most dangerous, as "multipath echoes" can be highly coherent and cause total destructive interference with the "direct" path signal from an interrogator or transponder.

Structure Reverberation

Structure reveberation is a major area of concern in offshore installation position monitoring as coherent strong multipath signals are often associated with underwater structures and can cause destructive interference of the direct signal. This is particularly the case with large smooth surfaces like riser sections, jacket legs or template structures where signals will be reflected with very little energy loss, although the target strength of a particular object does depend on its shape and the incident angle. The consequences of this reverberation can be minimized by correct choice of hardware mounts, frequency band (higher the better) and geometry. If in doubt about how to properly mount acoustic equipment, consult the equipment manufacturer.



If in doubt about noise - *GET IT MEASURED*



Signal to noise ratios for various acoustic systems

Hardware Design

The following sections discuss several aspects of hardware design to include transducers, battery packs and source levels.

Transducers

Transducers are basically a ceramic element encased within a waterproof housing. The transducers are designed to be very efficient when transferring acoustic energy to electrical energy and *vice versa*. The exterior of a transducer is designed to have a very good "impedance match" to the water in which it is designed to work. This ensures maximum energy transfer from the ceramic element to the water column. If a transducer "boot" becomes dirty (covered in grease or WD40) a layer of air can become trapped between the water and the boot and absorb precious energy. Air is a great acoustic energy absorber!

Transducers are designed to have a particular type of directionality. An LBL transponder will be required to talk to both the surface and other LBL transponders on the seafloor– these units usually have "Omnidirectional" transducers. An ROV responder working with just a USBL system will always be talking to the surface, so these are usually delivered with directional transducers. Their directionality will be approximately +/- 15 degrees off their vertical axis. Deep transponders for noisy DP applications need both upward source to get into the noisy vessel and sideways source to work with seafloor ROVs and other beacons. In this instance a compromise will be the best option.

Battery Packs

All transponders, pingers and responders require a power supply. If they are to be powered from a battery pack a decision has to be made as to which type. Batteries normally used include:

- Lithium (two lithium technologies are regularly used)
- Alkaline
- Nickel-cadmium (NiCd)

Lithium has an environmental/shipping overhead. Disposal has to be via a regulated facility. Shipping is tedious and limiting for remote locations when speed is needed. Lithium has the greatest energy density and shelf life.

Alkaline is very readily available, has a reasonable energy density and minimal environmental impact. For operations of normal duty cycles and deployed lives of less than six to nine months, alkaline packs will work for most applications.

Nickel-cadmium is a very cost-effective choice for short duration operations when a charge can be completed. Self discharge and memory problems are a concern. One of the more practical concerns is thinking that you are ready for the job and no one has charged the eight transponders. With only two chargers this could take 3 days!

Source Level

Why isn't equipment designed to have enough source to overcome all of the noise problems discussed above?

An increase of 3 dB is equal to a doubling of power, which also equals half the battery life! Transponders and surface equipment are designed with optimal power levels, so the equipment should work in most circumstances. If a particularly noisy vessel is to be worked on, then units can be switched into high power for the duration of the job. All modern equipment now has variable power (source levels). This capability is acoustically commandable, which ensures that the optimum power level is used for the particular operation and battery packs are not consumed pointlessly. Too much power can also cause positioning problems when a previous ping is still reverberating in the water column. This can be a problem with LF systems at high power in deep water.

Case Study - Deep Water DP Drilling

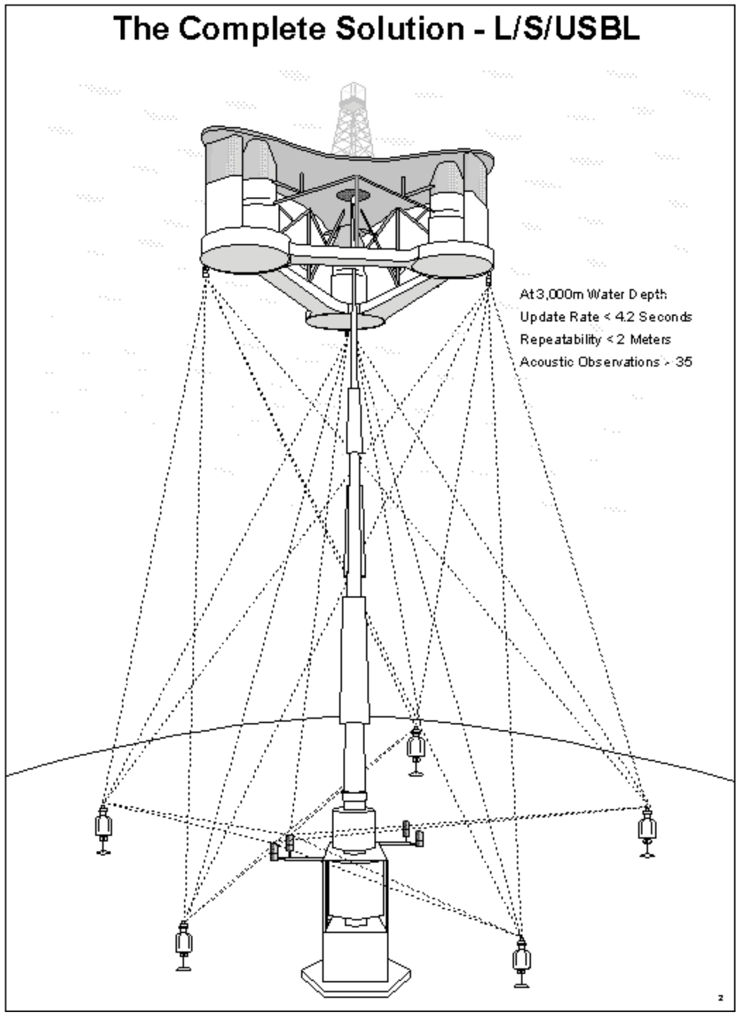
One of the more topical subjects today is the continuing demand for deep water drilling capability. Many rigs have recently gone through upgrades, doubling or tripling their water depth capabilities. At the deep end of this market are the rigs with an 8,000 to 12,000 ft (2,438 to 3,658 m) capability.

DP systems work best with very regular raw data, updates (the acoustic systems talk to the DP system via a DP telegram). DP systems will usually have multiple position reference sensors–DGPS, Electrical or Acoustic Riser Angle Monitor, Long Baseline and Short or Ultra Short Baseline acoustic positioning systems.

The DGPS is very useful for determining a surface position, but in 8,000 ft (2,438 m) of water the only requirement for the DP system is to keep the rig, at the surface, over the stack and minimize the differential angle on the flex joint. Providing an absolute position relative to the sea surface helps, but this position is not relative to the stack.

Acoustic positioning systems are very good at this but suffer from several drawbacks. USBL and SBL system accuracy is a function of slant range–the deeper the depth the worse the positional jitter–the more the vessel "hunts". USBL and SBL do provide good update rates. LBL provides very accurate position fix, but as the water depth gets greater, the slower the update rate. In 8,000 ft (2,438 m) of water the slant range to a transponder will be approximately 9,200 ft (2,804 m), a two-way range from the surface to the transponder to the surface will take approximately four seconds. The DP system usually requires data every second.

One of the other major concerns for this application is the noise at the surface and the long range from the transponder back to the surface. A DP drill ship is not an acoustically quiet vessel. To overcome this problem, and other operational concerns, Sonardyne has developed a system with a transceiver (RovNav) at the seafloor on the stack.



The RovNav transceiver will be working in a relatively quiet acoustic environment. It will also be much closer to the seafloor array. The source level required from the seafloor transponder into the RovNav will be significantly less. This will not only guarantee solid position updates, but it will also lengthen the battery life of the transponders greatly. The acoustic cycle time is now almost halved. The other major benefit of this system is that it is a combined Long and Ultrashort Baseline system (L/USBL). In good weather the surface hardware can stop interrogating the seafloor array and the RovNav can just be used as a very high source level responder from the stack to the surface. This will provide regular positioning updates of lesser accuracy than the combined L/USBL system, but without the use of the battery packs within the seafloor transponders.

Nothing is free! What additional problems does this RovNav on the stack cause? It costs more and it requires a power supply and communication link from the BOP stack to the surface. However, the main concern to date has been–what happens in the case of a disconnect?

In this instance the system is required to stop ranging into the RovNav and change the transponder power levels back to high power and position the vessel at the surface from the array. This requires knowledgeable operators and good ergonomic design to ensure minimal operator “load” in what will probably be a stressful time for the DP operators.

In most cases today, any system provided to these type of installations will be a dual redundant system. Such systems have to share databases, range data, transceivers and power supplies. These systems also have to be reviewed and accepted by the class institute that is responsible for the vessel.

What is just over the horizon?

Sonardyne is a leading manufacturer of systems in this area, and according to Keith Vickery, the following new developments are on the horizon:

Digital Signal Processing (DSP)

Recent development programs have been looking at signal processing technology and what benefits are available. This has resulted in a major step forward in system performance. Yet to be proven in all applications, Sonardyne believes that they will obtain 8-dB signal to noise improvement and possibly an increase of four or five times in range resolution performance. This could mean an MF system that will provide conventional EHF range resolution and work on noisy ROVs to full ocean depth.

System Integration

The DP market, and possibly the survey market, is demanding more system integration. That is, more capability within one system. The L/USBL system and L/SBL systems are just the start of this. Future systems will be much more plug and play. A single system will be able to have multiple transceivers plugged in and will simultaneously provide position updates for multiple targets within the water column. An example would be DP outputs while installing subsea structures and positioning ROVs with a single system, simultaneously.

Less Knowledgeable Operators

As a result of system integration and a “black box” approach, more DP operators, ballast control engineers and maybe even ROV pilots will be able to provide survey type services with these integrated systems. Thus, a L/USBL system will be able to be calibrated and used to install a template by the normal crew on a DP field support vessel. This will impact the survey companies, but if not managed and supervised will allow vessel operators to sell services that they are not qualified or really capable of providing.

Summary

Unfortunately, following the perfect theoretical world just discussed comes the *practical real world***.** Thus, when working with acoustic positioning systems offshore, it is guaranteed that situations will arise that cause problems within the acoustic positioning systems. Hopefully, the skill of the operator and the design of the system will eradicate the majority of these for most operations, however, be prepared for the following:

- “All of a sudden we just lost tracking!!”

Ever changing geometry will result in changes in the reverberation (multipath) conditions.

- The Mexican jumping bean syndrome - “The darn ROV is jumping all over the screen!!”

Ever changing geometry will result in variable ranges, beam patterns, signal level variations and presentations of noise sources.

- “When the weather picked up we lost acoustics completely!!”

When thruster power levels increase, noise levels and aeration will usually increase in the water column. This results in low signal to noise and high attenuation of acoustic signals. The prudent operator will complete noise trials in a realistic situation.

- “Who left that @#%!&! pinger on the stack?”

More and more acoustic positioning systems are being used closer and closer together. Be aware of what other systems are operating around your project. Time share if necessary.

Underwater Viewing Systems

Optical Viewing Systems

The fact that there is no universal underwater vehicle system has been proven again and again, with purpose built systems becoming the rule. This same fact applies to the design of an optimal underwater viewing system–there is no universal system. Depending on the application, one viewing or inspection technique will out perform the other. Low light TV provides long distance viewing whereas color provides contrast, but requires high illumination, which results in high back scatter, however, the camera produces good close in resolution. Add to this equation sonars, which can view at long distances with limited resolution, and laser imaging systems that can cut through turbidity, obtaining camera like images, and the techniques available grow considerably.

In addition, modern ROV systems have the capability of carrying 10 TV cameras and operating 5 or more simultaneously. With the advent of components such as Focal Technologies' fiber optic video and data multiplexer, up to 8 uncompressed video channels and 15 bi-directional data channels may be transmitted on one single-mode optical fiber. ROV umbilicals may carry up to 12 fibers, of which several are designated as spares in case of breakage.

Thus, with such dramatic potential, larger systems will have a combination of several types of underwater viewing and documentation subsystems, and smaller vehicles will carry what they can, but what they do carry must be matched to the task at hand. The following sections will address the different types of viewing systems, provide details on their use, and examples of their capabilities.

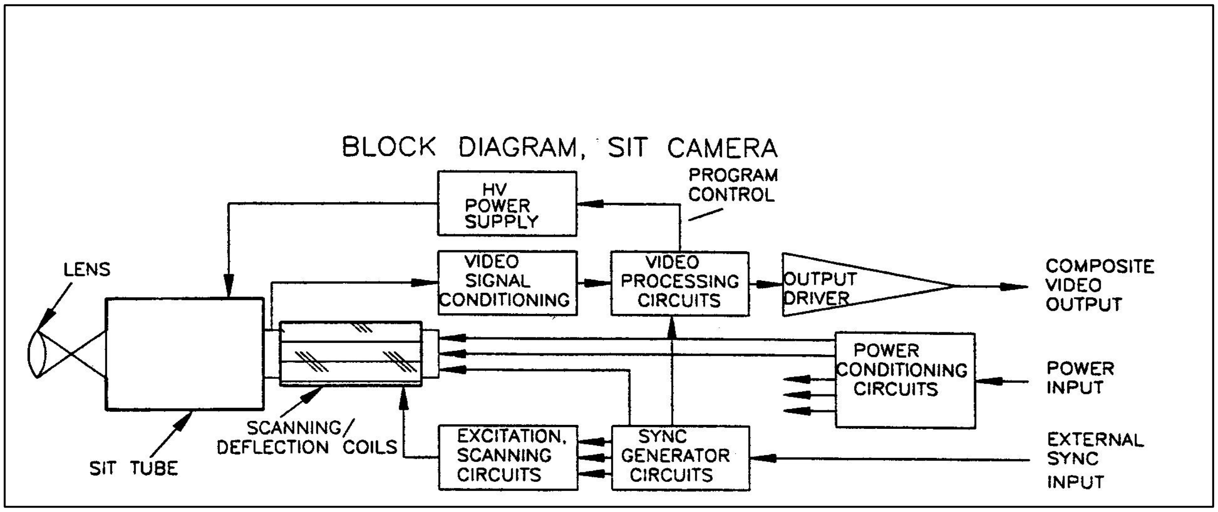
Television/Video

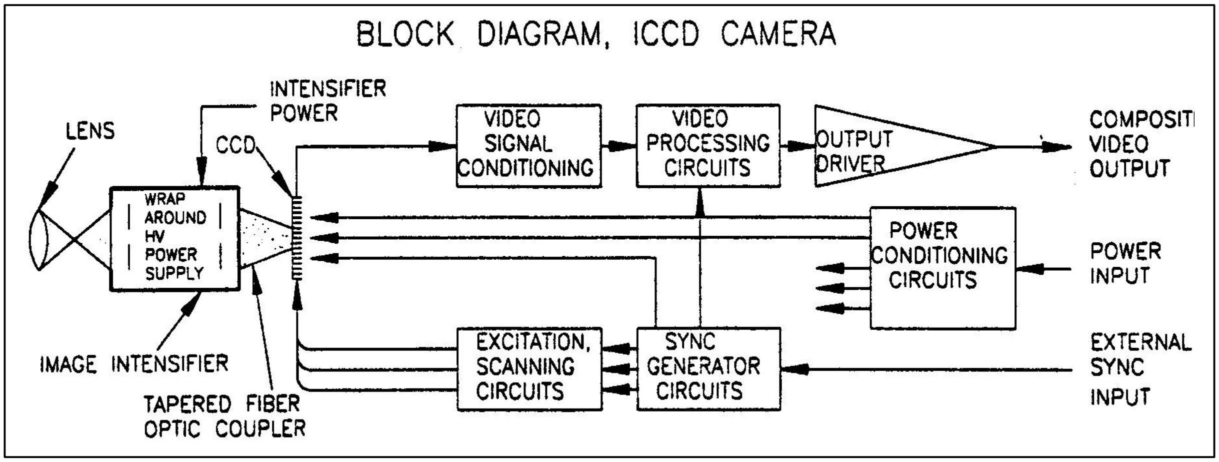
Unlike film type photographic equipment, closed circuit television/video systems provide real time feedback and documentation to the operator–an absolute necessity for direct operator control of the system. Although the images acquired do not have the very high resolution available with hard copy photographic images, the operator has the warm feeling that he does have good documentation of the object being investigated without the concern of returning to the site because of a problem with the photographic camera. And, new frame grab technology can give the operator a hard copy of the video image, albeit at a lower resolution than other techniques.

Cameras in use include Silicon Intensified Target (SIT), Silicon Diode Array (SDA), and Charge Coupled Device (CCD). Low-light-level cameras have been used in the underwater environment for more than 25 years, with the SIT the most commonly used. New image intensifiers with upgraded features are now available for use with ICCD (intensified CCD) assemblies and are likely to become the sensors of choice in the future. The main performance improvement in these intensifiers is in the higher sensitivities available, which can significantly improve low-light performance, and provide a larger variety of spectral response.

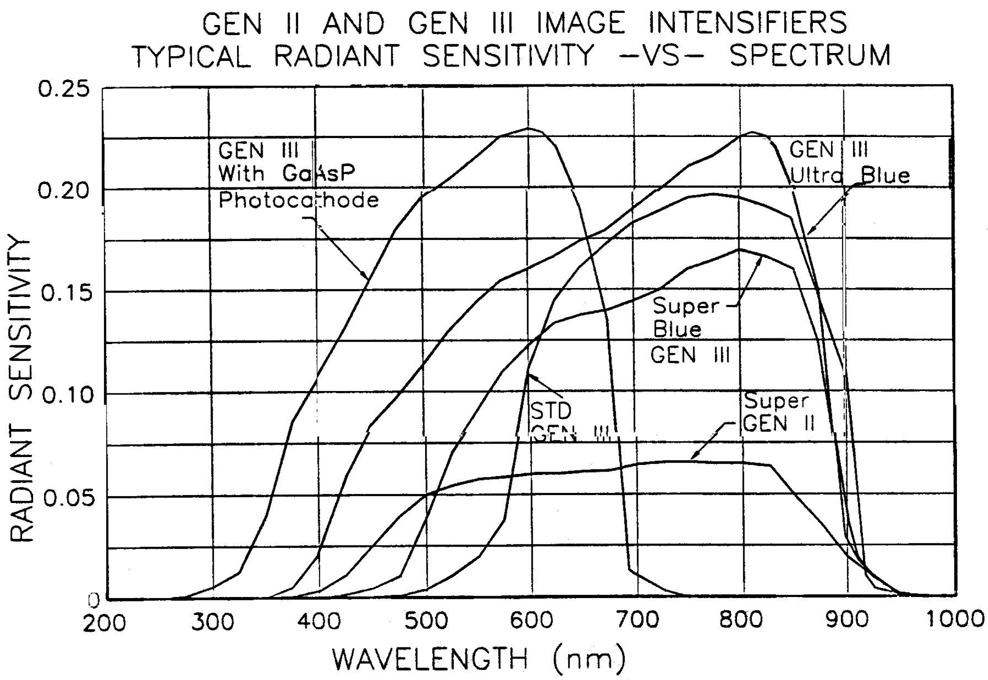
Low Light Level Cameras

Low light level (LLL) cameras operate with illumination levels hundreds and even thousands of times less than conventional tube or CCD cameras. In one form or another, these cameras use a vacuum tube device called an "image intensifier" in conjunction with an image sensor assembly. An intensifier receives a low light level image on its faceplate and electronically amplifies the image that is delivered to an output faceplate. Intensifiers have been employed widely in night-vision binoculars and telescopes used by the military and other agencies. The SIT tube assembly includes an intensifier furnished with and directly coupled to a vidicon type image tube. On ICCD cameras, the intensifier is normally a separate device that is installed between the camera optics and a CCD sensor. Either a lens, or more frequently a tapered fiber optic coupler, is used to transfer the image from the intensifier to the CCD faceplate. Start up of the ICCD cameras is virtually instantaneous.





The SIT tube is the most commonly used device in LLL cameras. In addition to having sensitivity approximately 1,000 times greater than a conventional CCD camera, it also features high horizontal resolution, about 600 TV lines, one of the highest available with present day image intensified cameras. The photo cathode of the SIT tube has been improved over the years to reduce blooming effects and increase the light level that can be accepted without damage. In addition, the SIT tube has nearly optimum spectral response for underwater applications; with full output at 500 nanometers wavelength, it nearly matches the so called color “window”–minimum light attenuation in the blue-green part of the spectrum is about 500 nanometers wavelength. And, LLL cameras with new generations of intensifiers (STD GEN III, GEN III Ultra Blue, etc.) are available with a variety of photo cathodes featuring increased spectral response in specific bands.



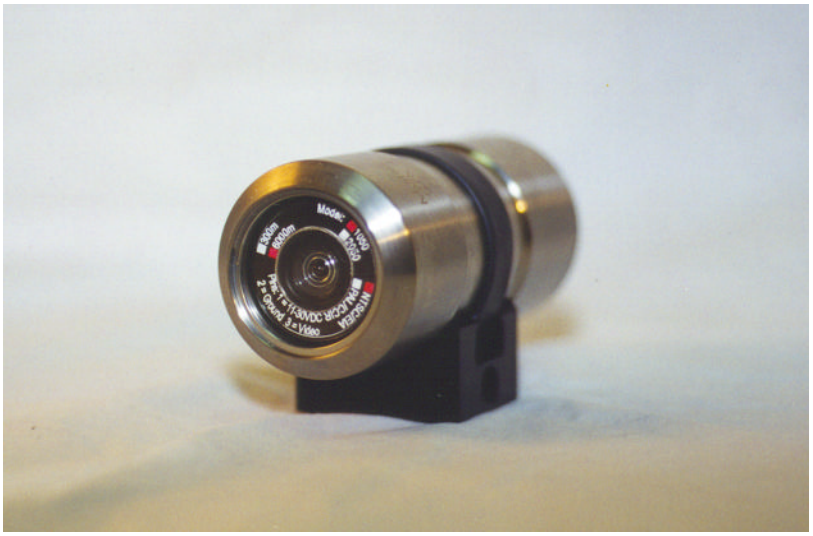
There are several benefits of LLL cameras. Lighting is a major item in the power budget for many television systems, thus LLL cameras can significantly reduce this budget. This is an especially important consideration in battery powered vehicle design, and also for interconnecting cables, where their size and weight can be reduced. LLL cameras include significant reductions in size, weight, and power consumption and improvements in reliability, stability and repeatability.

A good example of the reduced size of present CCD cameras is Applied Ocean Physics' MINICAM line of cameras. The 6,000 ft (1,829 m) depth capable monochrome camera sports a CCD with 550 lines of horizontal resolution, is 2.2 in (5.6 cm) in diameter and weighs 0.25 lb (0.1 kg) in water. Color versions are about twice as long. The era or the manipulator wrist camera has arrived.

Applied Ocean Physics' 6000-foot MINICAM

It was only a matter of time before the LLL cameras became integrated with the computer. Insite Systems, in their Gemini camera (see photo), has combined advances in computer and surface mount technology through the use of an onboard microprocessor which enables the user to control virtually all of the camera's internal settings to optimize performance under any lighting condition. Operating in a Windows environment, the operator, with the click of a mouse, can adjust the video level, high frequency compensation, AGC, iris setting, or a number of other controls within seconds. The camera can also be commanded to return to factory settings. Another unique feature is the ability to trouble shoot the camera. Built in diagnostics monitor the camera and it can even be linked via modem directly to the factory for on-line diagnostic assistance. Obviously, such technology will really springboard underwater cameras into the computer age.

Insite Systems Gemini



DSPL Multi-SeaCam

DeepSea Power and Light (DSPL), in addition to their line of underwater lights, offers underwater imaging solutions with its excellent line of cameras. The Multi-SeaCam (above), the company's newest camera, offers unprecedented versatility and ease of use. Designed as an inexpensive, small, fixed focus camera, the Multi-SeaCam uses a single housing design for shallow and deep applications, as well as monochrome and color versions for each depth rating. Designs for 984 ft (300 m) use Delrin and 19,685 ft (6,000 m) use titanium.

Using the same housing design for all applications makes future upgrades easy, and allows ROV operators to standardize all their applications with one electrical and mechanical interface. ROV operators find the Multi-SeaCam particularly useful as a manipulator or tether-monitoring camera. An additional benefit as a manipulator camera is the sapphire port. Sapphire is nearly impervious to scratching (except with a diamond), and holds up extremely well in the high-impact working environment of a manipulator.

Another innovation of the Multi-SeaCam is its "manual on a label," by which field or stockroom personnel can instantly identify key camera features by merely looking at the front of the camera. The features are printed on a label under the sapphire port, indicating model type, depth rating, video format, and pin-out. Serial numbers are laser-engraved on the housing for inventory tracking.

Regardless of the type of camera chosen, today's advanced designs are allowing compact and efficient systems that provide an excellent end product.

Still Cameras

The Basics of Underwater Photography

Underwater Photography (This section was adapted from the publication "Offshore Photography" written by Charles L. Strickland, the founder of Photosea Systems Inc. Photosea is a registered trademark of Kongsberg/Simrad Ltd.)

Although you will probably never have direct need to apply the physics of underwater optical systems, it is helpful to understand the basic principles that affect light underwater. In underwater photography, light is transmitted through water and through a window into air–the camera. This section will hopefully give you a better understanding of terms such as refraction, dispersion, absorption, scattering, and others.

a. Refraction and Dispersion

As a light ray passes from water to air, it is refracted in accordance with the equation

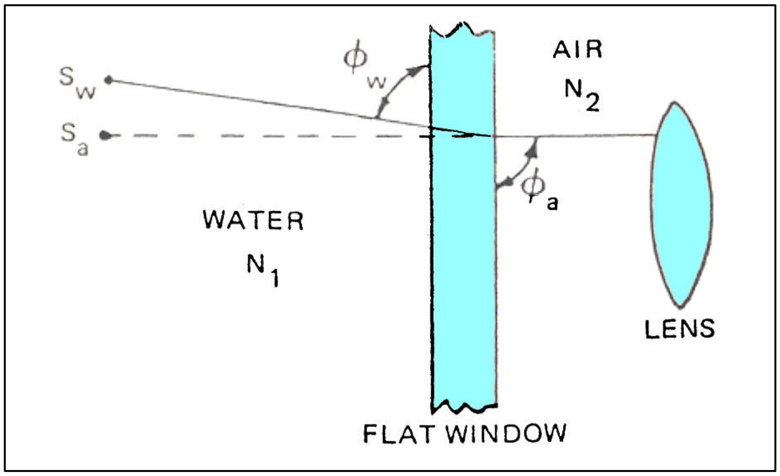
$$\mathbf{N_1} \sin \varnothing_1 = \mathbf{N_2} \sin \varnothing_2$$

in which $\mathbf{N_1}$ and $\mathbf{N_2}$ are the refractive indices of water and air respectively and $\varnothing_1$ and $\varnothing_2$ are the angles between the ray and the normal to the surface in the corresponding cases. If light passes from water into glass or plastic and then from the glass or plastic into air, this equation is used successively at the two surfaces. This situation is simplified if the glass or plastic has surfaces that are plane and parallel to each other. Then the properties of the window do not affect the final result, which becomes

$$\sin \varnothing_a = \mathbf{N} \sin \varnothing_w$$

in which **N** is the refractive index of water relative to air, approximately 4/3 (see the following figure).

Rays originating from $\mathbf{S_w}$ after passing through window appear to come from point $\mathbf{S_a}$



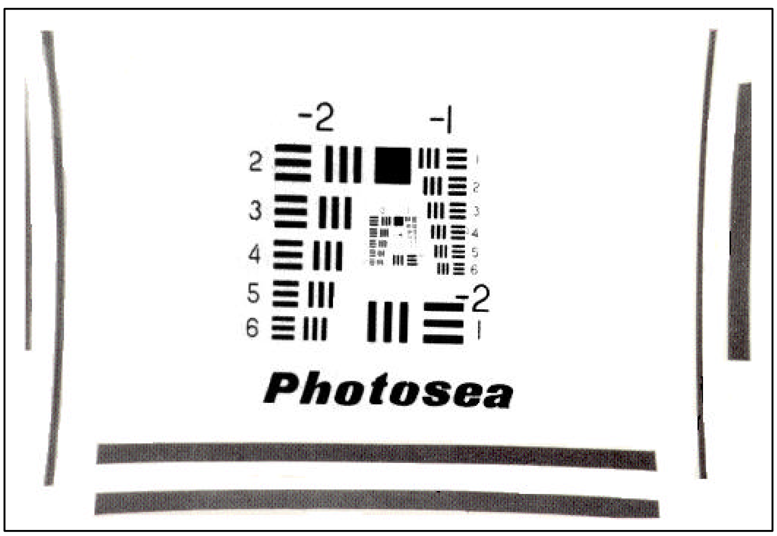
When viewing an object in water through a plane window, unless the lens is corrected, refraction causes focus error, field of view error, and distortion as follows:

Focus Error - Rays diverging from a point at a distance **Sw** from the window appear, after they have passed through the window, to come from a distance **Sa**, so that

$$S_a = S_w / N$$

Field of View Errors - A ray coming to the window at any angle of incidence other than zero will leave it at a wider angle. Thus, an optical system such as a camera, which has a given angular field of view in air, will have a small angular field in water. In addition, an object, which would produce an image of a certain size if it were in air, produces a larger image if it is in water. The lens appears to have a longer focal length, approximately 4/3 that in air. This is why subjects always look magnified when wearing a diving mask underwater.

Distortion - Rays from points forming a rectangular grid in water will not seem to come from a rectangular grid after they have passed into air. There will be "pincushion" distortion in a lens that is not corrected for underwater use.



Note the "pincushion" distortion in this underwater photo taken with an uncorrected lens.

b. Absorption and Scattering

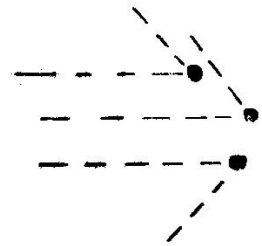
Light is attenuated as it passes through water in accordance with the relation

$$I/I_o = e^{-kx}$$

where I_o is the initial intensity of the light; **I** the intensity after scattering and absorption in the water; and **k**, the attenuation coefficient, is the sum of the absorption coefficient α

and the scattering coefficient β. Both α and β depend upon the wavelength of the light and upon the material dissolved and suspended in the water.

β - reduction in light due to scattering from particles in water



α - reduction in light due to absorption

Observers agree that the absorption and scattering in clear ocean water are essentially the same as in clear distilled water, that some dissolved matter increases the absorption, and that suspended matter increases scattering.

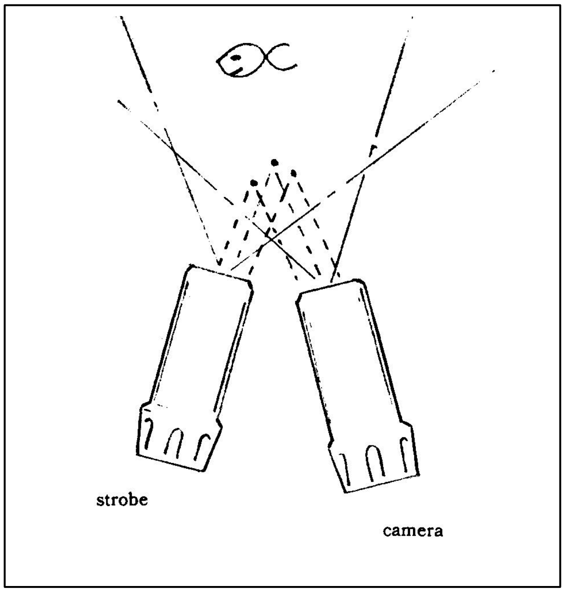
Both absorption and scattering present difficulties when optical observations are made over appreciable distances in water. Scattering is the more troublesome, as it not only removes useful light from the beam, but also adds background illumination. Compensation for the loss of light by absorption can be made by the use of stronger lights, but in some circumstances, additional lights can be degrading to a system because of the increase in backscatter.

These circumstances are analogous to driving in fog; the use of “high beam” headlights in most cases causes worse viewing conditions than “low beam” headlights.

Keeping unnecessary light out of the water between the object being photographed and the camera can reduce the background illumination caused by scattering. This can be accomplished by separating the light and camera, and in very turbid water using two or three lower powered lights positioned efficiently instead of one higher-powered light helps the situation.

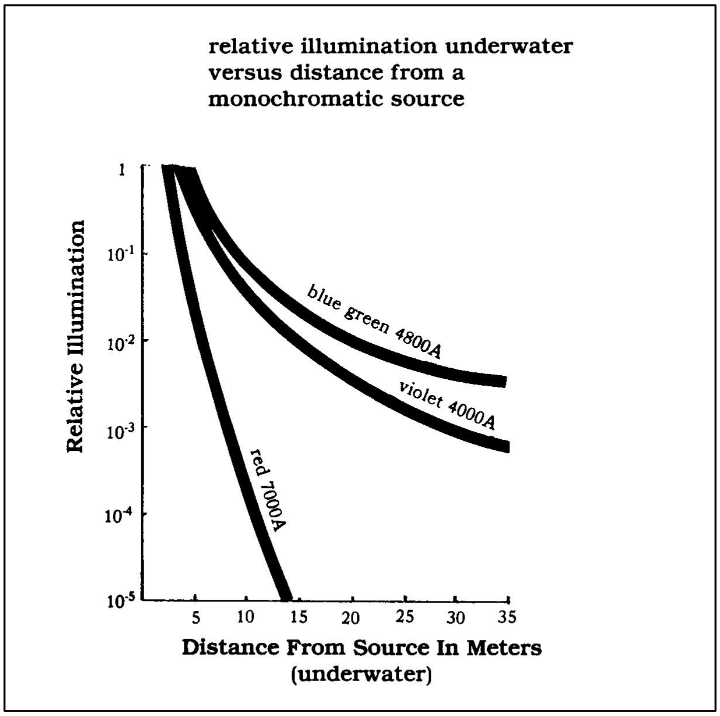
Objects a few meters from a camera can be clearly imaged in ocean water, but unlike air, even in the best ocean water the clarity is sharply reduced for distances even as small as 16.4 to 32.8 ft (5 to 10 m). In coastal waters where “backscatter” is encountered, the distance at which usable photographs can be obtained or visual observations made, may be as small as a meter or two.

In some coastal water the effect of backscatter can reduce visibility or useful photo range to only a meter or two. Keeping the light source away from the front of the camera helps the situation.



c. Water "Color" Absorption

In addition to the basic effect of light intensity reduction in water due to absorption, the matter is further complicated by the fact that absorption is a function of color. Red light is absorbed approximately six times faster than blue-green light in water. This is why long distance underwater photographs are simply a blue tint without much color.



The graph shows the severe attenuation of red light (7000 A) compared to that of blue-green and violet.

Even in the clearest surface water, reds are virtually non-existent in ambient light beyond 13 to 16 ft (4 to 5 m) depth. This situation is greatly improved in underwater photography by using powerful strobe lights with the camera to get more “red” light to the subject and thus yielding a more color balanced photograph.

Lenses

a. What is an f-stop?

The beam of light passing through a lens is limited by means of a diaphragm or “stop.” This aperture is called an iris and can control the light admitted to the film. An “f-stop” is the relationship between the diameter of the lens opening and the focal length of the lens as follows:

$$\frac{1}{f} = \frac{d}{F}$$

where ***f*** represents the f-stop or aperture, d the diameter of that aperture, and ***F*** the focal length of the lens.

Each reduction of one f-stop halves he amount of light admitted through the lens. In other words, if the f-stop is changed from 4 to 5.6 (closing the aperture) the light reaching the film at the “5.6” setting is only 1/2 that of the “4” setting.

Then why the crazy numbers 4, 5.6, 8, 11, 16, etc.?

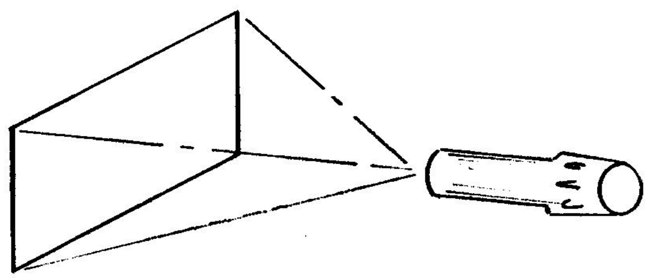
You will note that each stop in the f-stop progression is the previous number multiplied by 1.4 (the square root of 2). If you recall from basic math, to find the area of a circle you multiply the constant π (3.14159) by the radius R squared. Since the radius is the diameter/2, if that measurement is then doubled, the area is quadrupled; if it is halved, the area is reduced to 1/4. Since the exposure-producing light is entering through this area, exposure is affected in the same way. Therefore, to ‘double’ or ‘halve’ the light you can’t ‘double’ or ‘halve’ the diameter, you must change it by 1.4 (the square root of 2).

As you will see further this ‘doubling’ or ‘halving’ makes the relationship between f-stop, strobe power, and film ASA speed very easy to work with.

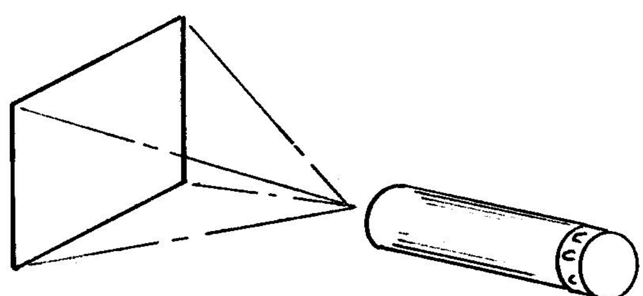
b. Angle of View/Area of Coverage

All camera manufacturers normally list the angle-of-view (in water) of the camera lens system, and from this information the area-f-coverage at various distances can be calculated using simple trigonometry.

Remember, if the horizontal and vertical angles-of-view are different (as with 35 mm format cameras), the area covered will be a rectangle. For 70 mm cameras, which normally use a square format, the horizontal and vertical angles-of-view are the same.

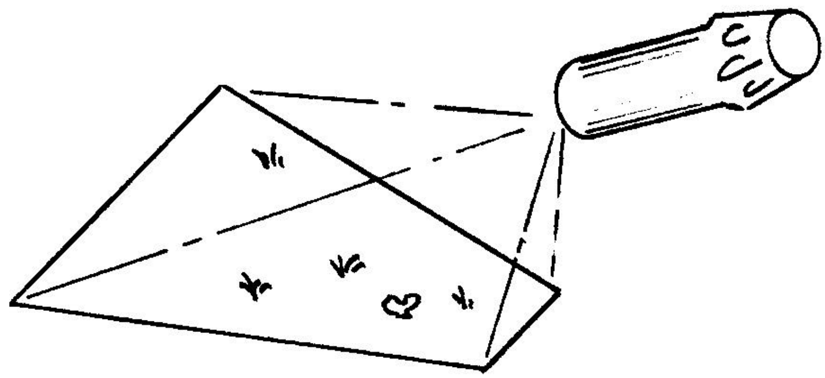


35mm cameras cover a rectangular area with the same ratio as the negative $\frac{24}{35}$ mm or $\frac{1 \text{ vertical}}{1.5 \text{ horizontal}}$



Most 70mm underwater cameras cover a square area. Horizontal and vertical angles are the same.

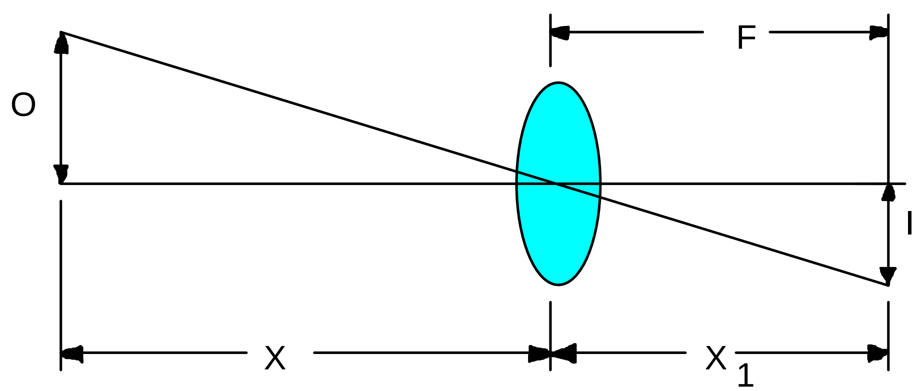
Planning a photo mission and calculating the area-of-coverage of your camera system can get complicated if the camera is not looking straightforward or straight down. For example, if the camera is viewing the bottom at an angle such as from an ROV or towed sled, the area-of-coverage will be a trapezoid as shown in the following figure.



The mounting angle can result in a 'trapezoidal' viewing area

c. Image Size

The size of the image on the negative produced in a camera depends upon a number of factors, as shown in the following figure:



Factors governing image size.

As the two triangles in the previous figure are similar we can write:

$$\frac{I}{O} = \frac{X_1}{X}$$

Therefore: $$I = O\frac{X_1}{X}$$

Expressing this in words - the size of the image **I** produced in a camera depends upon the size of the object **O** and on the ratio of the image conjugate $\mathbf{X_1}$ to the object conjugate $\mathbf{X_2}$. Except for very near objects, the image conjugate $\mathbf{X_1}$ does not differ greatly from the focal length. In these circumstances we can write:

$$I\ (\text{Image}) = O\ (\text{Object})\ \frac{F\ (\text{focal length})}{X\ (\text{Distance of object from lens})}$$

This formula for calculating the size of an image on the negative can be valuable to you when planning a photographic mission if you know the size of the object to be photographed and want to know its actual size on the negative.

Film

There are a large number of film emulsions available from several manufacturers throughout the world and individual preference seems to vary greatly from photographer to photographer. But underwater, the choice becomes more limited because of the spectral characteristics of water and the limited amount of light available.

a. Film Speed

Every film is rated on the basis of its light sensitivity (ASA). The higher the sensitivity (higher the ASA number), the less light is needed to make the correct exposure on the film.

A 'doubling' or 'halving' of the ASA will 'double' or 'halve the amount of light needed for proper exposure (the "1/2" rule again). For example, Ektachrome 200 will take twice as much light as Ektachrome 400 to get the same exposure (as you can see a one-'stop' increase in f number, or doubling the power of your strobe light can be the same as doubling the film's ASA speed.).

Then why not just use very high speed film (ASA 1000, 2000, etc.), which would allow me to use low powered strobes and increase my depth-of-focus?

Like everything else–with film, you don't get something for nothing. You have probably hard the term 'grain' used when talking about film or picture quality. The higher the ASA speed the more 'grain' in the film and the lower the quality of the resulting picture, particularly when blow-up prints are made.

Many professional ‘topside’ 35mm photographers use Kodachrome ASA 25 which has extremely fine grain and excellent picture quality even with large prints. Although this low ASA speed film is not practical underwater because of the limited light conditions, a good compromise is ASA 200, such as Ektachrome 200 which is still a fine grain film, but with moderate speed.

Also, when using ‘low power’ lights you encounter the ‘red’ problem again. Without red light, color photography simply does not contain as much information.

b. Film Types and Color Balance

There are two basic types of film emulsions:

- ‘**Negative’ film** - You must make a print before you can properly view the subject matter (example: Kodak Tri-X black & white film, Kodacolor or Vericolor color film).

- **‘Positive’** (sometimes called color-reversal film) - You can view the subject matter directly on the film (example: Kodak Ektachrome or Kodachrome Color slide film).

Films also vary in their sensitivity to different parts of the color spectrum. for example Ektachrome is a ‘blue’ sensitive film, Kodachrome more ‘red’ sensitive, and Fugicolor more ‘green’.

In addition, some types of films are ‘balanced’ for artificial lighting. For example, you may see a film type marked ‘Tungsten’. This film has been balanced for use with artificial tungsten lights and would not produce good photography in daylight.

High-powered Xenon strobe lights produce a ‘daylight’ color spectrum and are only to be used with ‘daylight’ balanced film. Since 95 percent of all offshore photography is accomplished with strobe lights, you would normally only use ‘daylight’ balanced film.

c. 35 mm vs. 70 mm Film

One of the basic questions asked when selecting an underwater camera is–should I use 35 mm or 70 mm film and why?

First of all, as in ‘topside’ photography, 35 mm is by far the most popular film format used in underwater photography. It has many advantages:

- Cameras are normally smaller, lighter, and less expensive than 70 mm units.

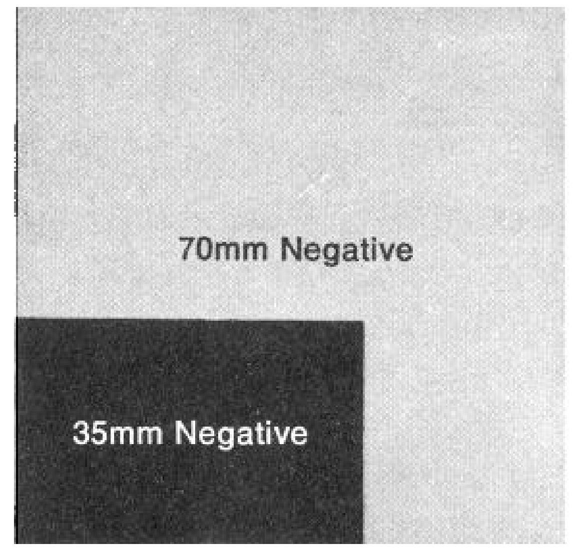
- 35 mm film is readily available almost everywhere and less expensive than 70 mm film.

- 35 mm film is easier to process offshore.

They why 70 mm?

Again, as in ‘topside’ photography, most professional underwater photographers use the 70 mm format if at all possible. Because of the much larger format (with comparable lenses), higher resolution can be achieved because of the increase in negative area. The 70 mm film format provides an image area over 3-1/2 times larger than the 35 mm format.

When photographing remotely from a frame of ROV it is quite often desirable to have the largest practical negative format so subjects in various parts of the negative can be ‘cropped’ and enlarged if required. Also, because of much larger area with 70 mm film, more detail is possible, allowing enlargements of considerable size without loss of resolution. Direct contact prints can be made and negatives can be examined with out viewing aids.



In most applications, the 70 mm format will provide more detailed photographic information.

There is no question that a properly corrected 70 mm underwater lens system will produce superior photographic results when compared to any 35 mm system. It’s simply a question as to whether the photographic mission planned can justify the additional cost.

d. Film Selection

As you have seen, the choice of film can be wide-ranging and sometimes confusing. It is recommended that the different films should be experimented with and the one that satisfies the basic mission requirements should be used. Generally, if you stick with one type of film, you will get consistent results and better pictures.

Here are some recommendations for films to use offshore and the reasons behind them:

Black & White

- Kodak Tri-X Pan Professional Film or equivalent

- Fine grain, ASA 400
- Good exposure latitude combined with high speed
- Readily available in standard cassettes, and 100 ft (33 m) professional rolls of both 35 mm and 70 mm.
- Easy to develop and print offshore.

Color

Ektachrome 200 (daylight) or equivalent

- Fine grain color reversal (positive) film with ASA speed of 200, enlargements can be made without ‘grain’ effect.
- Subject matter can be directly viewed on film, and slides can be projected. Color prints can be easily made using type ‘R’ or Cibachrome process.
- Blue spectral characteristics of this film match water ‘filter’ effect very closely.
- Can be push processed to ASA 400 with excellent results.
- Readily available in standard cassettes or 100 ft (33 m) professional rolls of 35 mm or 70 mm.
- Easy to develop offshore using Kodak E-6 process.

e. Film Developing

It is not the intent of this publication to cover the subject of film processing, but if you are planning an offshore photographic operation, quite often processing ‘on-site’ will be required. Film developing can be done manually or by fully automatic machines depending on your particular requirements–and budget. One major difference normally encountered during offshore operations is that large capacity cameras are normally used. Because of the high cost of each photo mission, anywhere from 100-800 photos are normally taken per dive. Thus film developing systems, whether manual or automatic, should be capable of handling long lengths of film. For example, (100) 35 mm photos represent approximately 12.5 ft (4.8 m) of film.

Exposure Control with Electronic Strobe Lights Underwater

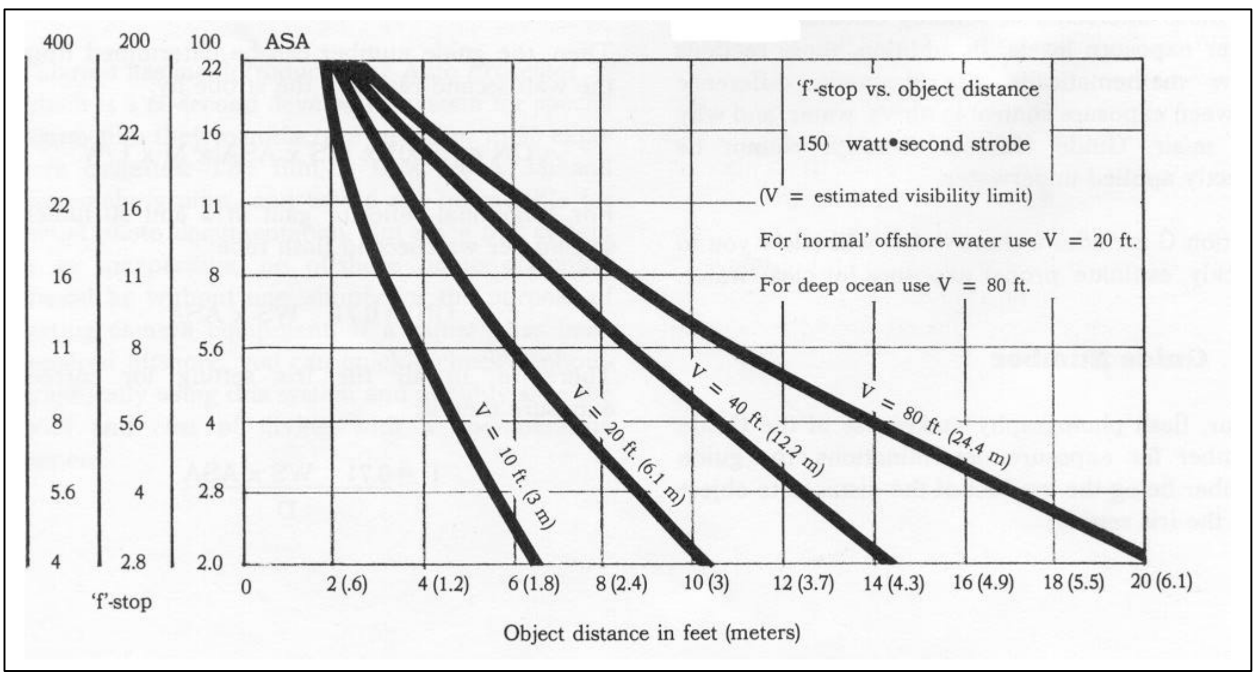
As previously explained, taking pictures underwater can be affected by many variables–water clarity, absorption, scattering, color sensitivity, etc. Understanding the difference in exposure control underwater vs. ‘topside’ photography can help insure that you produce consistent and successful photographic results offshore.

Remember, underwater photography is substantially improved through the use of electronic flash illumination for the following reasons:

- High illumination levels are available to offset the normal attenuation of light in water.
- A consistent level of illumination simplifies the problem of obtaining proper exposures.
- Strobe lights provide the balanced illumination necessary for color photography, as the reds are virtually non-existent in ambient light at depths beyond 13 to 16 ft (4 to 5 m).

a. Estimating your proper exposure underwater.

There is a dramatic difference between exposure control in air vs. water, thus the in-air 'Guide Number', which is determined by the flash rating and film speed, cannot be directly applied underwater. Without going into the method of actually calculating underwater exposure levels, a more simplistic chart will be provided. The following chart of f-stop versus object distance for various film speeds (using a 150 watt-sec strobe) is a good 'starting point' for estimating proper exposure. This chart assumes no ambient light–in high ambient light conditions, the iris should be stopped down further than the settings shown to compensate for the additional exposure. The amount of iris adjustment will depend on the levels of ambient light in your particular application, but normally would only be 1/2 to 1 'f' stop.



b. Color Compensation

Proper color compensation of photographs can also be a very complex situation underwater, and at best you will only be able to properly correct at one distance range.

The values of the ‘one stop attenuation distance’ derived by visibility estimates are for blue-green light in clear water, because the red light is almost totally absorbed at relatively short distances. The ‘one stop attenuation distance’ for red light is 3.5 ft (1.1 m) in the clearest ocean water. At 14 ft (4.3 m), the red light is down 4 stops over what it would be in air. In comparison to blue-green light, red will be down one stop more than the blue-green for every 4 ft (1.2 m) distance increment to the object. This fact can be used to color correct the water factor with red filters on the camera when using flash under water.

A CC5R filter with an ASA rating of 38-38-0 passes red light unattenuated and attenuates blue and green light by the equivalent of 1.2 stops. Thus, this filter will balance the blue-green light to the red light level at a distance of 5 ft (1.5 m). Two such filters will correct for 10 ft (3 m), etc. It must be noted, however, when using this filter that one additional stop is required for each 4 ft (1.2 m) of distance over what would be used without the filter. Therefore, it is necessary to use high-powered strobes and fast films if color is desired more than a few feet away.

You will note that the optimum color correction occurs at one distance only and imbalances develop as the object is displaced from that distance. Furthermore, as the filters can correct only in 5 ft (1.5 m) increments, imbalances will occur at distances between those that give optimum correction. Therefore, if you attempt to ‘color correct’, it is suggested that you only do it at one selected distance, and at close range.

Digital Cameras

The tremendous advances in digital imaging technology have now made their way into the subsea arena. Early systems, which cost as much as $150,000, have now been replaced with highly portable, reasonably priced equipment. Digital cameras provide the user with the ability to capture real-time images (delayed by a few seconds to allow for processing) that can be transmitted from the vehicle to the topside operator–a capability that does not exist with film cameras. Such a capability eliminates the long wait to reacquire the film, the cost of processing the film, and most importantly, the ability for the operator to see what he acquired while still on location, thus providing the ability to return for another set of photographs.

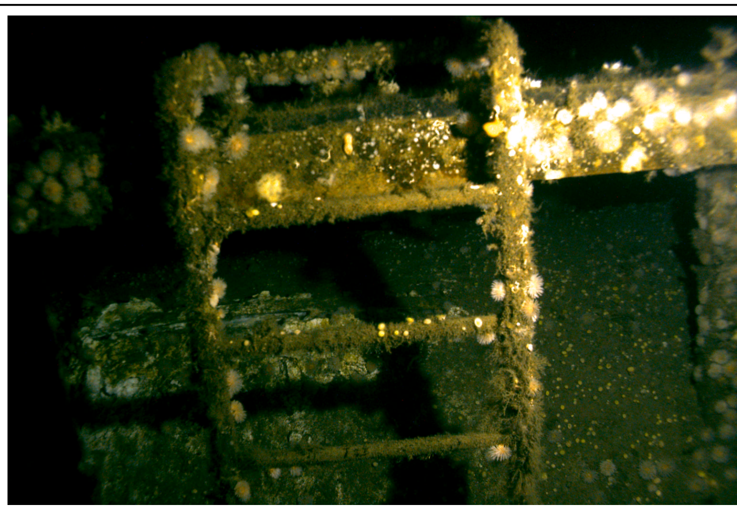
With the data in digital form, on site processing can be performed, and if desired, the images can be transmitted to other locations electronically. Post processing, which can be performed with commercially available software packages, can include electronic zoom, edge enhancement, contrast stretching, color alteration, scene exposure corrections and other manipulations of the image. Such processing can often reveal information not obtainable through traditional imaging methods.

Benthos, Inc, one of the leaders in developing cameras for underwater applications has produced their DSC 5010 digital still camera. Based upon the state-of-the-art KODAK MEGAPLUS 1.6 camera, the DCS 5010's image provides 1.5 million pixels of information for the sharpest digital image possible. In either color or black and white, the camera's dynamic range provides a gradient detail of 1,024 light levels, with selectable equivalent film speeds ranging from 60 to 750 ASA.

The standard DSC system comes in two housings, one with optic and imaging electronics in a small housing for ease of placement, while the camera control, power supply, and telemetry electronics are housed separately. The camera can be operated over various telemetry configurations including coaxial, twisted pair or fiber optic.

The following images were taken with the color DSC 5010 installed on SubSea International's *Examiner* ROV. All images were acquired using a 100 watt-sec strobe at 500 ft (152 m) depth in the North Sea.

DCS 5010 digital image of a docking cone (right) and a ladder (below)



Lighting Considerations

Some of the basics of underwater lighting have been covered in earlier sections. These issues covered water absorption and backscatter. In brief, backscatter can be reduced by separating the camera and light to minimize common volume backscatter. Common volume backscatter is the illumination of suspended particles that create a bright foreground, thus reducing image contrast and visibility. Minimizing backscatter can be resolved by simple trial and error.

Selective absorption refers to the rates of absorption underwater that different colors of the spectrum have, and thus different levels of penetration through water. Red light is rapidly absorbed, whereas blue-green light has the least rapid absorption rate.

One other aspect of illumination is the color temperature of the lamp itself. Color temperature is measured in degrees Kelvin (K). Most underwater lights use tungsten halogen incandescent lamps with a color temperature of 2,800-3,400 degrees K. The dominant wavelengths at this color temperature are red. Light at this color temperature comprises primarily red wavelengths, and is rapidly absorbed in water, reducing penetration of the light and also the range at which true color imaging is achieved. This is fine for some ROV applications where the intent is merely to navigate or produce videotape of close-in work for documentation. However, for professional video imaging applications, HMI® lamps provide the best illumination. Higher color temperature light also reduces backscatter, particularly at longer distances underwater as the ratio of near scattered light (more red) is lower relative to light coming in from the object of interest farther away.

HMI lamps are arc discharge lamps in which the luminous arc burns in a dense vapor atmosphere comprising mercury and the rare earth halides. HMIs have a "daylight" color temperature around 5,600 degrees K, similar to natural sunlight. Light produced by HMIs has a higher color temperature (longer light wavelengths), and thus penetrates further, providing greater true-color illumination over a wide area. This makes HMIs an ideal illumination source for filming wrecks.

HMIs are also more efficient than incandescent lamps, producing 3-4 times more lumens per watt. Since there is no filament to break, they are less sensitive to shock and vibration. A separate electronic ballast regulates power input. Primarily used for documentary expeditions (such as the *Titanic*), HMI lights are gaining acceptance in the general ROV market as customers become aware of this technology and demand the best video recording possible.

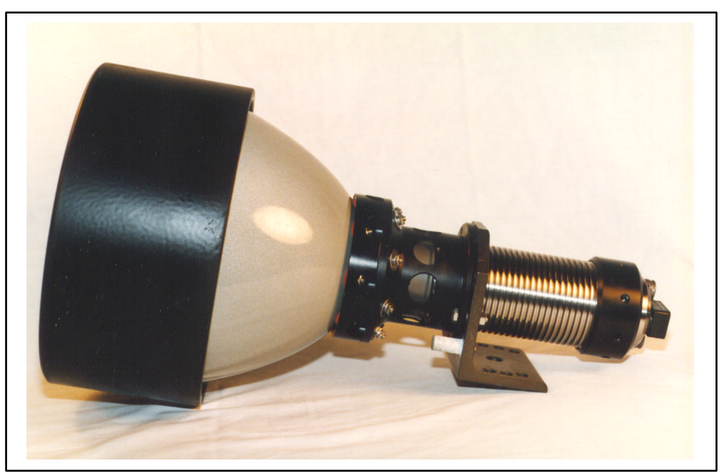
DeepSea Power & Light (DSPL) is a leader in underwater HMI technology, and millions around the world have viewed famous wrecks and biological wonders of the deep courtesy of DeepSea's HMIs. Their HMI lights have illuminated the *Titanic* for several documentaries, including the Imax film *Titanica*, James Cameron's Oscar-award-winning movie *Titanic*, and the television documentary of the attempt by the R.M.S. Titanic, Inc. to raise a piece of the *Titanic*. Other famous wrecks recorded for public documentaries include the *Edmund Fitzgerald, Lusitania*, and US and Japanese ships in Iron Bottom Sound off the coast of Guadalcanal. In 1998 Bob Ballard, well known underwater explorer, recorded images of the *U.S.S. Yorktown*, sunk at the battle of Midway during World War II.

Nearly every major oceanographic institution around the world has used HMIs on their submersibles and ROVs to document their discoveries. These include the US Navy's *Sea Cliff* and *Turtle*, Woods Hole's *Alvin*, Russia's *Mirs 1 & 2*, JAMSTEC's *Shinkai 2000, Shinkai 6500,* and *Kaiko*–which explored the Mariana Trench at 36,089 ft (11,000 m) depth–and MBARI's and HBOI's vehicles, to name a few. Subsea International, of Belle Chase, LA, installed HMIs on its *Hammerhead* 1 and 2 ROVs. National Geographic, The Discovery Channel, and A&E have produced television documentaries of famous wrecks and undersea wonders filmed with HMI lights.

DeepSea's standard HMI light is 400 W, and comes in 3,281- and 19,685-ft (1,000- and 6,000-m) versions. A 1,200-watt model, rated to 19,685 ft (6,000 m), is DeepSea's premium HMI light, which is primarily used for filming of high profile subjects (e.g., *Titanic, Yorktow*n).

DSPL 400 W HMI SeaArc2

DSPL 1200 W HMI SeaArc2



Complementing DeepSea's HMI lights are its metal halide high intensity discharge (HID) lights. HID lamps are arc lamps, just like HMIs, but use a magnetic ballast instead of an electronic one. HID lamps can also be doped to produce different colors of the spectrum. DeepSea offers a choice of Daylight, Thallium-Iodide (TI), and ultra-violet. Daylight lamps produce a color temperature essentially the same as HMIs, 5,000-6,000 degrees K. TI lamps produce green light, which penetrates the furthest underwater, and are the best lamp for long-range piloting. Ultra-violet (UV) lamps used in conjunction with UV filters are useful for finding oil leaks.

DSPL 400 W Ultra-violet SeaArc2

To satisfy the need of customers who want both HMI lights for videotaping and an HID TI lamp for navigation, yet don't want two types of ballast, DeepSea developed a hybrid TI lamp that can operate on an electronic ballast (TI/EB). JAMSTEC's *Shinkai 6500* has six HMI lights and one TI/EB light, all operating from the same electronic ballast.

HMI and HID Daylight lamps produce essentially the same spectral output for imaging purposes, and share other similarities. Lumens per watt are essentially the same. DeepSea uses the same housings for each type of lighthead, so size and weight are not an issue. The electronic and magnetic ballasts differ in shape (HMI ballasts use a metal housing, HIDs use an oil-filled diaphragm), but are roughly the same weight. Re-lamping costs and technique are about the same.

But there are differences that will guide a customer's selection. HMI have a higher color-rendering index, which refers to the "whiteness" of output. Whiter is better for color imaging. HID lamps are nominally 5-10 times the lamp life of HMIs. HMIs warm up in 1-2 minutes; HIDs take 3-4 minutes. HMIs have hot restrike ability, which can be critical for an ROV. HIDs may take 20 minutes after power-off before the lamp can be restarted on a magnetic ballast. HMIs can be dimmed, but HIDs cannot. HID lights require AC power, whereas HMIs can operate on AC or DC. HMI systems are 2-3 times more expensive than an HID system because of the ignitor (which HID lights don't have), ballast, and other associated housing costs.

HID is recommended for applications where long lamp life is important, or lamps are left on continuously without off/on cycling. DeepTow photo survey vehicles, long duration ROVs, tourist submarines, and aquariums are examples. HID is appropriate where cost is a limiting factor.

HMI is recommended for applications requiring hot restrike, when frequency of lamp replacement is not a factor, and when only DC current is available (such as on a submersible). It is also recommended when customers demand the best underwater lighting available.

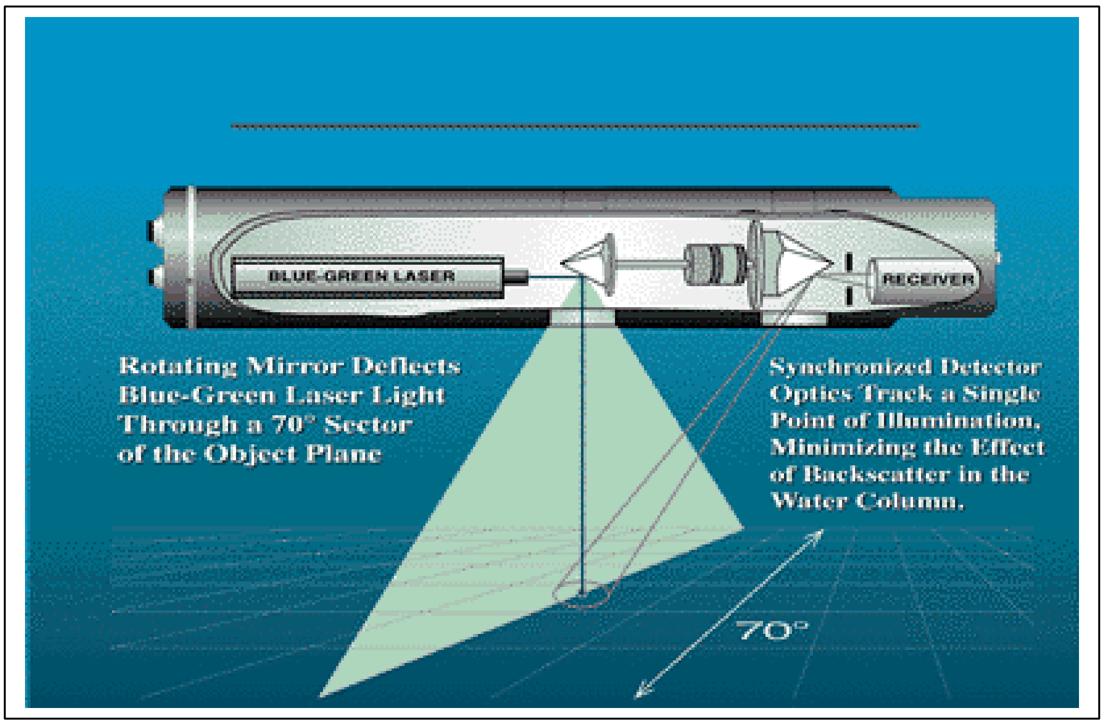
® HMI is a registered trademark of Osram.

Laser Line Scanners

One of the newest tools on the market is the laser line scanner, a device that works exceptionally well from a towed or moving platform for underwater search and/or surveys. The following section will provide an overview of the technology along with some recent applications.

Technical Description

The Laser Line Scanner (LLS), in its simplest form, is a sensor that takes advantage of a laser to concentrate intense light over a small area in order to illuminate distant targets and extend underwater imagery beyond that offered by more conventional means. The LLS builds up an optical image from a rapidly acquired series of spots on the seafloor, each sequentially illuminated by a pencil sized diameter laser beam which scans the bottom perpendicular to the direction of the sensor support platform. This technique minimizes the effects of forward scattered and back-scattered light. The resultant data are displayed as a continuous "waterfall" image that can be recorded on a standard video cassette recorder. Distinct frames can also be captured and used to generate mosaic images of seafloor features.



Laser line scanner concept

The above figure shows the primary elements of the basic LLS optical sensor concept. The optical sensor consists of subassemblies for the imbedded sensor control electronics, the laser, a scanner and a detector. These four subassemblies are integrated into a single physical unit and installed inside a watertight pressure housing.

The scanner subassembly is composed of two rotating, four-faceted mirrors, rigidly attached to a common rotating shaft. The illumination laser is oriented such that its output beam is incident on the smaller of the mirrors, deflecting the beam downward to the seafloor. The receiver views the seafloor reflected light, incident on the larger mirror such that it is actually tracking the output laser spot as it scans. The unscattered, unabsorbed light that manages to reach the bottom illuminates a small, localized area that is called the primary scan spot. As the mirrors rotate, the scan spot traces a continuous line across the bottom. When there is relative motion between the scanner and the target, perpendicular to the scan direction, then sequential scan lines will be displaced slightly and the target will be scanned in two dimensions. By synchronizing the scan rate with the forward velocity of the sensor, it is possible to control the spacing between the scan lines, ensuring that true image aspect ratios are preserved.

By sampling the output of the photo-multiplier tube within the receiver with mirror rotation, it is possible to build up a 2-dimensional reflectance map of the scanned area. When each new scan line is introduced at the top of the operator console display screen, it automatically displaces the last one at the bottom and a "waterfall" display is created. This gives the operator a realistic downward view of passing over the bottom in real time. A computer system executes the functional algorithms that control the process. Typical size for a LLS system is about 13.8 in (35 cm) diameter by 5.1 ft (1.6 m) long, with an in-air weight of 300 lb (136 kg). By using folded optics, it may be possible to shorten the length with a larger diameter to achieve better form factor for certain applications.

SAIC Laser Scanner during launch

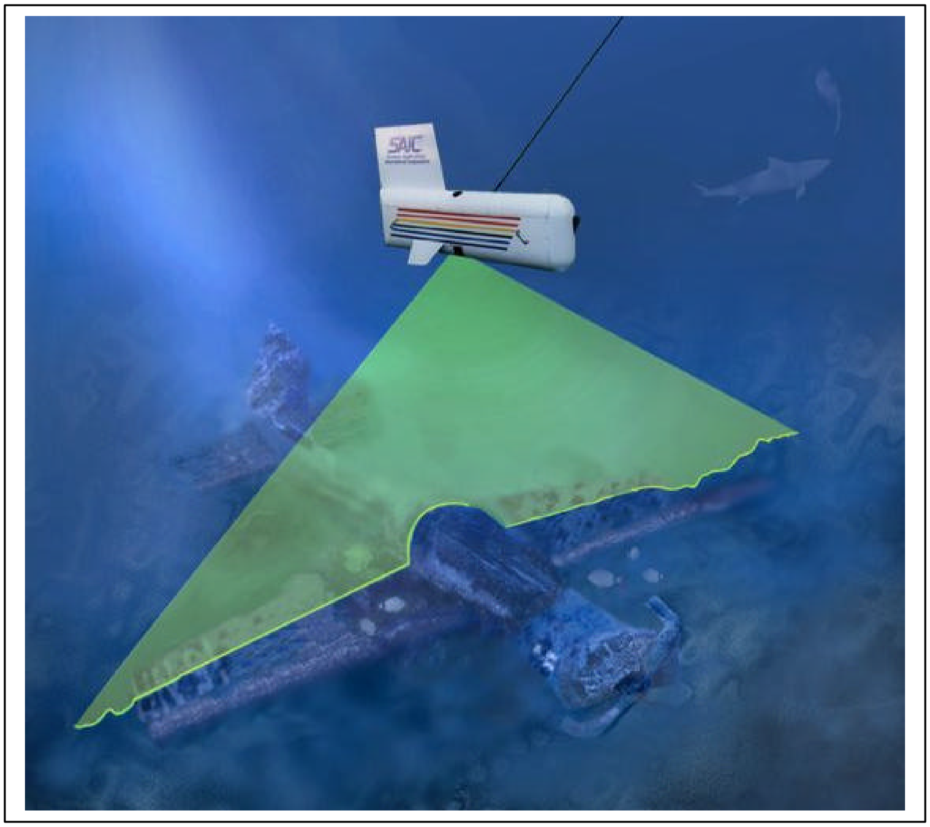
Applications and Operational Considerations

The niche where the LLS system seems to fit best is between sidescan sonar and video camera for search or survey operations. The ranges achieved by the LLS are considerably greater than for standard video cameras, but good area coverage is significantly less than for today's sidescan sonars. However, the good optical resolution offered by these systems makes them an ideal tool for applications such as limited area search, corridor surveys (e.g., pipelines and cable routes), and high resolution environmental surveys. As such, they have been historically transported on tow bodies, which have inherent long line stability with high data rate tethers to a topside processing and display console.

Stern launch configuration for the LLS towfish

Originally, LLS units were equipped with argon gas lasers and suffered from reliability and power consumption problems. Subsequently, however, the advent of solid state lasers has drastically improved the practicality of such systems in field use. The most widely used commercial LLS system today is a Northrop Grumman (formerly Westinghouse) solid state unit owned and operated for several years by Science Applications International Corporation of San Diego, California. This system has been shown to be extremely reliable in the field and has been used to survey sewer outfalls, shipping harbors, and aircraft debris fields. International survey interests have tested LLS systems for possible application, but initial capital costs have weighed heavily against widespread commercial use.

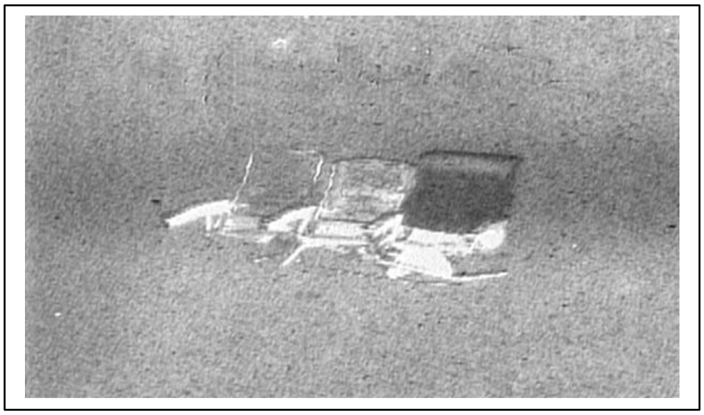
The US Navy has invested significant funds toward the development of the LLS as a mine-hunting tool, resulting in such advanced features as color imaging and higher resolution. The figure below shows how clearly the LLS can image search targets such as aircraft wreckage.



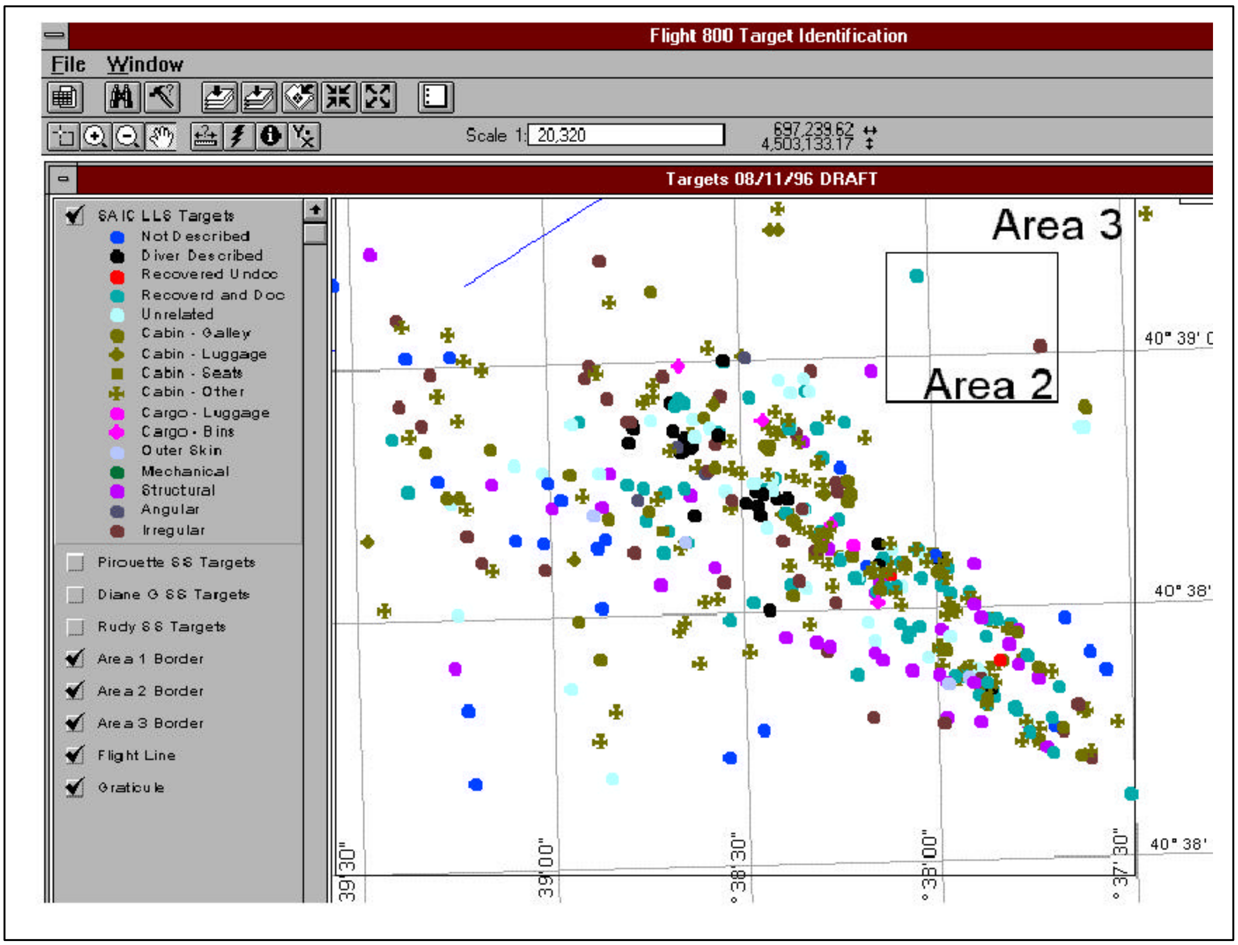
LLS imaging capability

Perhaps one of the best-known uses of the Laser Scanner was the search for wreckage of the ill-fated TWA Flight 800 off Long Island. The extent of the Boeing 747 debris field was enormous, with most of the pieces relatively small. Visibility was marginal and, although a great number of divers were used to recover such wreckage, their time on bottom under a no-decompression schedule was extremely limited. Sidescan sonar was of limited use, due to the soft bottom and large number of small aluminum pieces.

By integrating a good navigation system with regular parallel line coverage, promising targets were identified with the LLS and located precisely, enabling divers to drop on top of the proper pieces, secure them and return to the surface with outstanding efficiency. Further, an accurate map was generated on CD-ROM such that individual numbered targets on an overall chart could be called up and the LLS image of that target displayed, aiding greatly in the investigation (see figure of monitor). An example of the imaging ability is provided in the image of a seat section located during the TWA search.



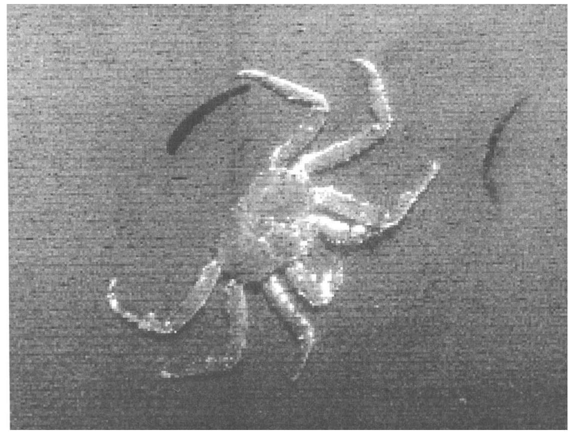
TWA seat section



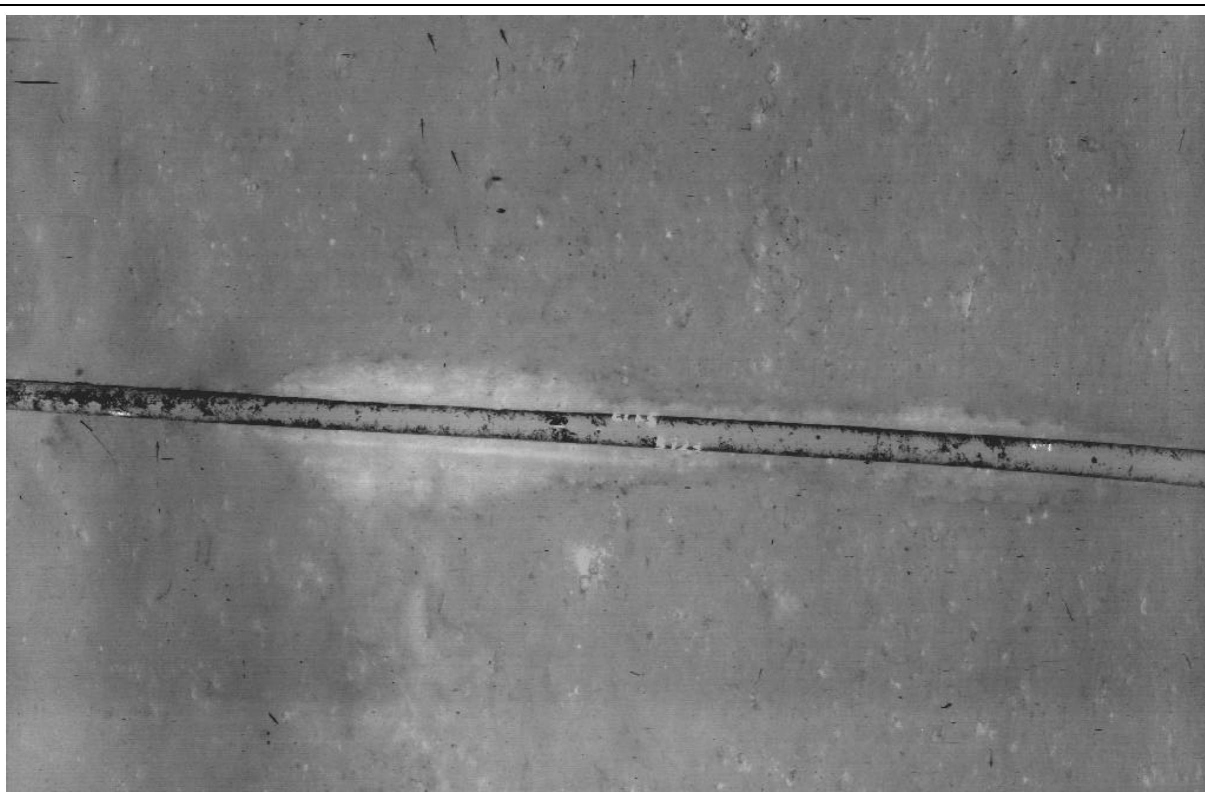
Monitor view of TWA search area

In addition, the LLS seems to have good potential for use with fishing interests and environmental evaluations. The following figure clearly shows a King Crab, demonstrating the potential usefulness for determining locations of such lucrative clusters in Alaska.

King Crab



The next figure shows a pipeline in the Gulf of Mexico, indicating a potential for pipeline survey using the LLS. Note the fish population in the image.



LLS image of undersea pipeline

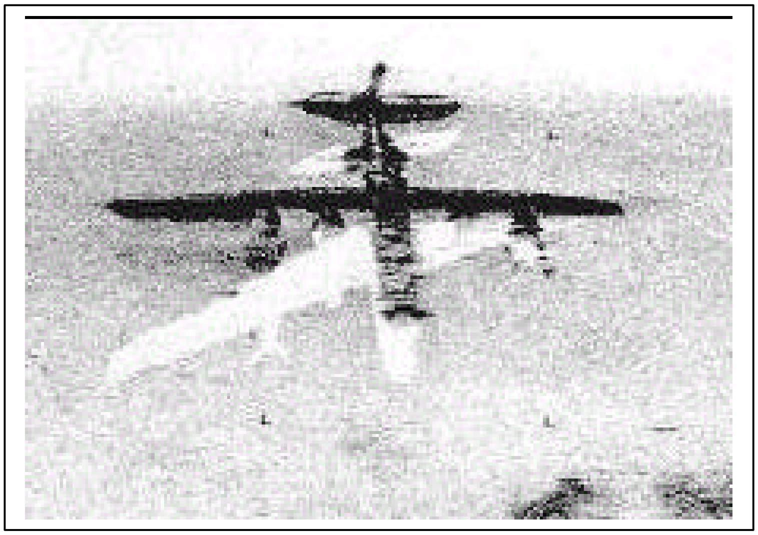
Summary

As with most tools, the Laser Line Scanner has distinct limitations as well as specific advantages. For example, one vital consideration for the two-dimensional display is that the vertical image axis is controlled by the forward movement of the sensor. Some "wobble" can be compensated for through computer-based error correction, but platform stability has a direct effect on the quality of the generated imagery. This has implications for any potential use with ROVs, which characteristically are designed more with maneuverability in mind than straight-line stability. Another drawback to LLS is that it typically requires motion in order to generate an image. This precludes stationary imagery. Efforts to "dither' the scan while the sensor is stationary have been experimented with, but such a procedure is not yet available for common use. Finally, the cost of LLS systems is substantial. Depending on a host of factors, a price tag of about $700,000 would not be uncommon. Day rates will vary, but a typical at-sea cost might be in the area of $2,500 to $3,000 per day, including two operators. The primary reason why such systems are not in wider use is because the perceived return on investment for most commercial operations is considered insufficient to justify the initial capital outlay. While the costs are not likely to come down soon, increased usage tempos brought about by advertising good results in a wider variety of conditions may improve the economics to the point where they are more common than at present.

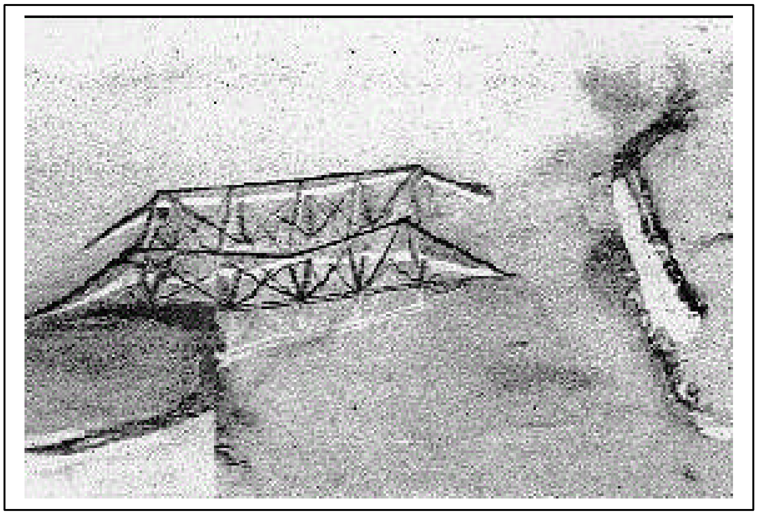
The LLS systems can be readily integrated with ROVs and, subject to the requirements for stable flight, used to good advantage to augment common video cameras. Maximum depths are currently limited to about 6,562 ft (2,000 m), primarily due to laser window structural limitations. Future trends include color imagery (Ocean News & Technology, June/July 1997) and improved resolution. All in all, the Laser Line Scanner is probably an underutilized tool that fills a gap between the range limitations of normal cameras and the resolution limits of side scan sonars.

Sonars: Our Acoustic Eyes

Light is absorbed over very short distances in the water environment. In working underwater, the lack of long range vision is a major limiting factor. In the early days of underwater work, performed manually, limited vision was not as significant because the diver could not move from one place to another very quickly. As robotics and instrumental intervention arrived at the worksite, the need to extend our vision became more vital. This becomes even more important because with our remote presence we can move more quickly from one place to another.



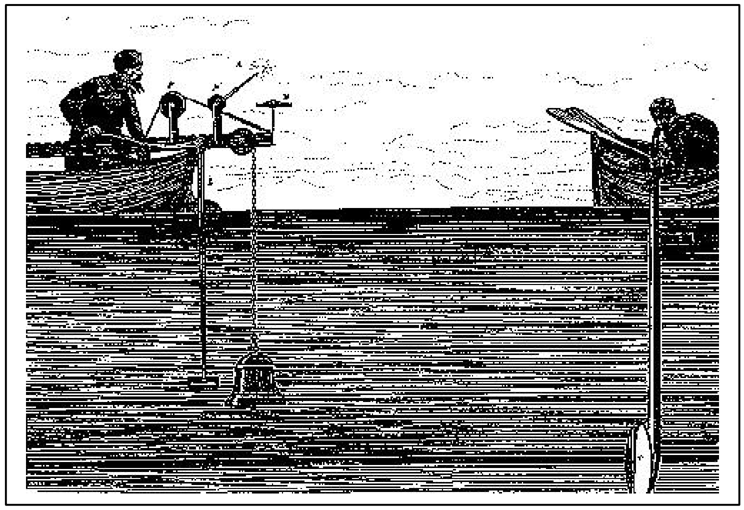
To meet the demands of "seeing" further underwater, engineers have turned away from the visible light spectrum and to another form of transmittable energy underwater: sound. Sound is also attenuated in the dense water environment, but not over as short a distance as light. Although the resolution of acoustic imaging does not approach optics, it does provide a remarkable extension of our vision, as the images of the aircraft and collapsed bridge in the figures on this page show.



Those working underwater, including oceanographers, marine geologists, and ROV Pilots now depend heavily on sound energy to transform the things we cannot see underwater into numbers, graphs, and pictures. The ROV pilot in particular requires that the imaging sonar provide him with accurate and quickly updated images. The instruments that transmit and receive these sound pulses have become sophisticated and more accurate in the past few decades.

Using Underwater Sound

Almost all of these instruments rely on the accurate prediction of the speed of sound underwater. Historically, mariners have realized that sound travels well in the high-density underwater environment. In the 1800s, scientists recognized that the speed of sound was consistent and, if predictable, might be a useful tool.



Underwater acoustics as a research discipline began in 1826, when Daniel Colladon measured the speed of sound in water on Lake Geneva, Switzerland. He positioned two boats 9.9 miles (16 km) apart. The procedure was to simultaneously set off a bright flash from the powder and hit an underwater bell with a hammer. His theory assumed that the light from the powder would travel the 9.9 miles (16 km) instantaneously, while the sound of the ringing bell would take some time to travel the same distance. Colladon timed the experiment with a stopwatch. By today's standards of electronics and high accuracy acoustics, these methods may seem very crude; however, his empirically calculated speed of sound underwater, at a water temperature of 46 degrees F (8 degrees C), came to within 0.21 percent of the currently accepted value of 4,718 ft/sec (1,438 m/sec).

Sonar

Underwater, sound transmission is limited. This is most notable in useable ranges. High-frequency sound energy is greatly reduced by seawater. Low-frequency sound energy is reduced at a much lesser rate. For instance, a sound pulse of 50 Hertz can be transmitted many thousands of kilometers in the ocean, but a pulse of 300 kHz, a common imaging sonar frequency, can be transmitted less than 3,281 ft (1,000 m).

A test of sound transmission was made in 1960, when underwater explosions from three, 300 lb (136 kg) amatol charges were triggered off the coast off Perth, Australia while an array of submarine listening sensors were strung off the coast of Bermuda. Submarine explosions are characteristically of low frequency, large bandwidth and high intensity and the resulting bubble collapse produce a wide range of acoustic frequencies. The higher frequencies are attenuated quickly but the lower ones propagate long distances. In the SOFAR (Sound Fixing And Ranging) Channel at a depth of between 1,969 and 3,937 ft (600 and 1200 m), sound propagates even further. Here, the physical aspects of the ocean bend an upward travelling ray back down and a downward traveling ray back up. So low frequency sound in this region will travel a long distance as it is refracted and re-directed at the top and bottom of this "channel".

Off Australia the explosion was set for a specific time. The oceanographers at Bermuda started to look for the incoming pulses at a preset time and indeed, the first acoustic rays from the explosion began coming in on time. There were many signals received over a period of several minutes because of the different ray paths taken by the acoustic pulses from the explosion. All three detonations were clearly detected in Bermuda–over ten thousand miles distant. The test became known as another "shot heard 'round the world'".

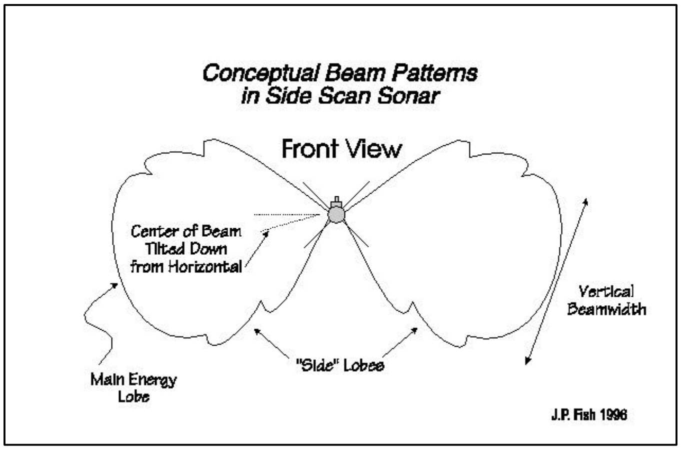
While the extremely long range that sound travels underwater is not applicable to high resolution imaging sonar (yet), the relationship between frequency and range has a wide variety of connotations in sonar. If the imaging sonar user wants to transmit, and receive, sound pulses at long ranges (and cover wide areas in a short time) a low frequency source is best to use.

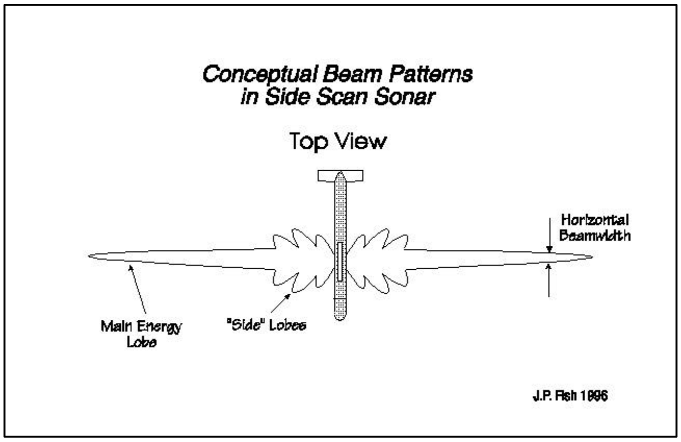
Unfortunately, the low frequency sound has longer wavelengths and often longer pulse widths (the amount of time the sonar is active). This provides lower resolution in the resulting information. If the need is to accurately image fine details, then it is preferable to use a higher frequency sonar. But these short wavelengths cannot be transmitted long distances and thereby limit the usable range. Often, the sonar operator will find that he must choose the usable frequencies for this application that will provide the best trade off between range and resolution. The following table provides the two-way working ranges of modern active and side scan sonar systems:

Frequency	**Wavelength**	**Distance**
100 Hz	15 meters	One thousand kilometers or more
1 kHz	1.5 meters	One hundred kilometers or more
10 kHz	15 centimeters	Ten kilometers
25 kHz	6 centimeters	Three kilometers
50 kHz	3 centimeters	One kilometer
100 kHz	1.5 centimeters	600 meters
500 kHz	3 millimeters	150 meters
1 mHz	1.5 millimeters	50 meters

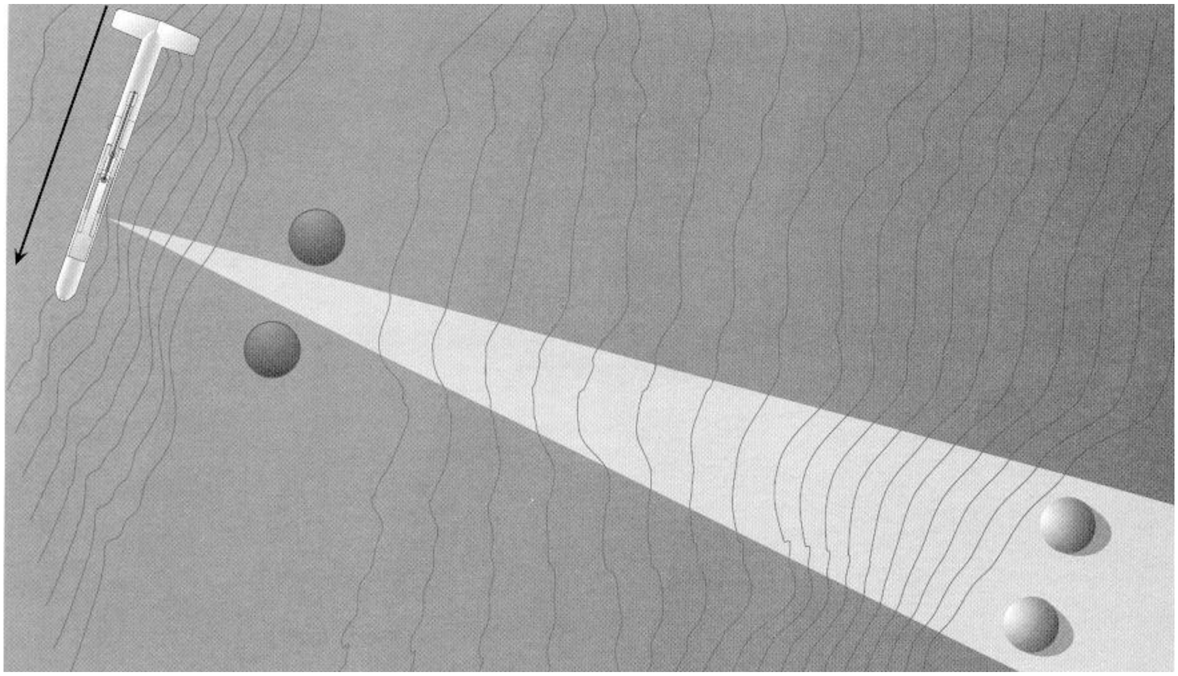
Sonar Beams

A typical side scan sonar is shown in the adjoining figure. When choosing a side scan sonar design, a number of sonar beam characteristics are important in determining the capabilities of the system. Not only is the frequency important but also the beam form or shape. A beam form is usually described as conical, fan shaped, or omni-directional. In order to gain useable information from an imaging sonar, the beam itself is specially shaped. It is this shape of the transducer (or the manner in which it is fired) that determines the shape of the resulting beam. Although there are hybrid systems in use that fall outside these parameters, usually the imaging sonar beam is directional and fan shaped. The size and shape of this type of beam, or beam angle, is described in degrees of an arc. For example, imaging sonars have beams that are between 0.5 and 2.0^{o} in the horizontal dimension and 25 to 60^{o} in the vertical dimension. In standard applications then, the beam will image a small slice of the underwater environment from the seafloor and up towards the sea surface as it propagates out from the transducer. With a 1^{o} horizontal beam angle, the imaging sonar is considered to be very directional in terms of overall sonar systems. This directionality, coupled with the fact that an imaging sonar receives its own reflections, has some implications on transducer stability or protection required from heave pitch and roll. The beam width at range is also an important feature, which helps to determine a system's resolving power. In this case we are concerned with the horizontal beamwidth, or the narrowest portion of the beam. As the sonar beam propagates away from the transducer, it undergoes beam spreading and the actual distance between the two outer sides of a

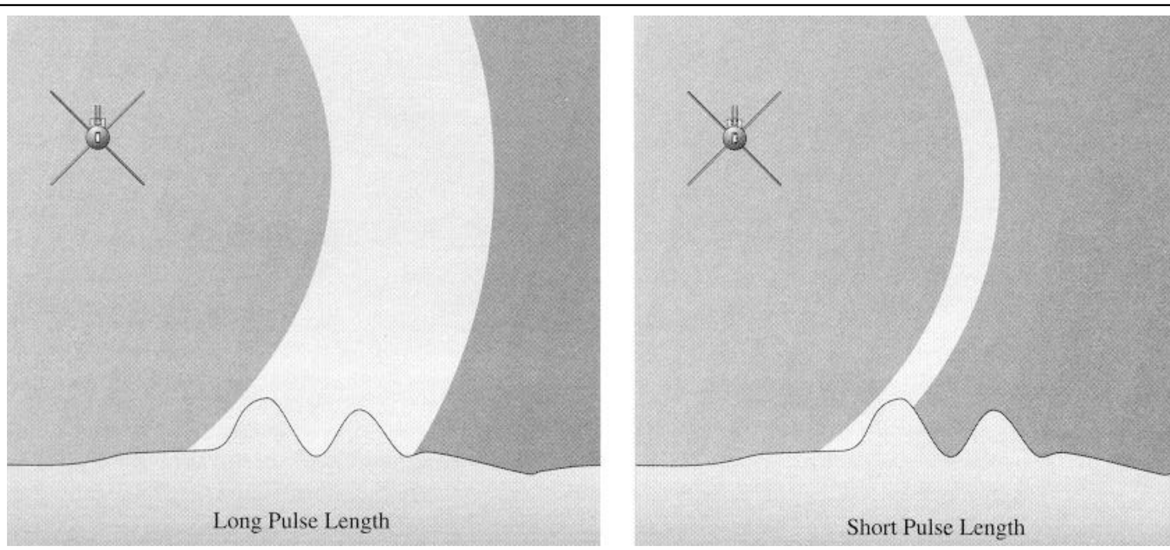




beam increases. At longer ranges the beam can become quite wide. In this manner, the sampled slice of the environment gets larger and the resulting image is of lower resolution.



Effect of range on sonar resolution



Effect of pulse length on resolution

Another important feature of sonar is the pulse length or the amount of time the transducer is actively transmitting. In some systems this is uncontrolled because the transducer is fired by the discharge of a capacitor. In others, the transducers are actively controlled by a "tone burst" and can be driven for shorter or longer periods of time. The longer a transducer is fired the longer the pulse length, which can result in lower image resolution, as shown in the previous figures.

Sonar Application on ROVs

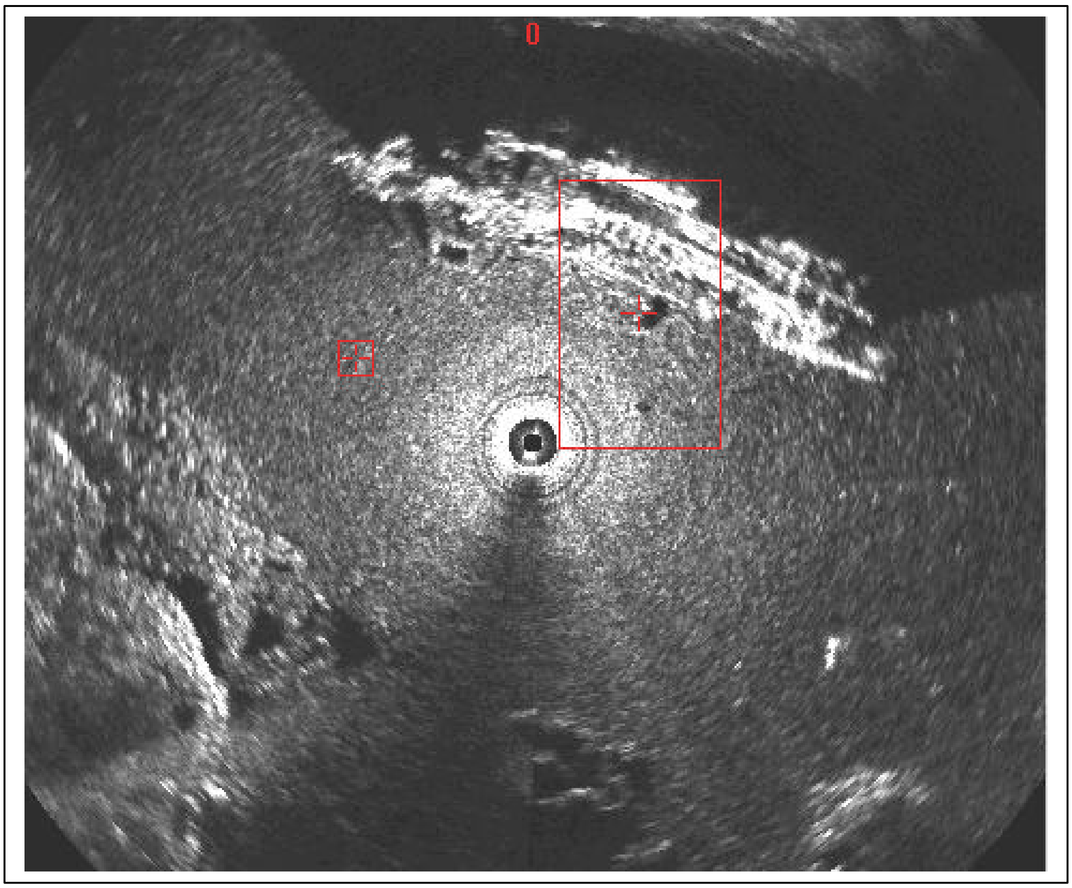
As applied to underwater vehicles, sonar systems in use today include mapping and collision avoidance types. Side scan sonar transducers can be mounted on the sides of a vehicle to provide a "map" of the seafloor from a vehicle. An advantage of side looking sonar on an ROV is that a long-range image can be provided out to the side of the vehicle's track. One disadvantage of side scan on a vehicle is that, while vehicles can be flown at low altitude along the seafloor, the side scan requires some amount of altitude in order to gain the necessary range. This problem is not new to the combination of long range acoustic and short-range optical imaging underwater. It is not always possible to fully utilize both simultaneously.

Almost every medium and large vehicle does utilize, however, a forward-looking sonar for navigation, collision avoidance and target delineation. These sonars are most often rotary sonars, commonly known as scanning sonar. They consist of a transducer head, which rotates and is mounted on an electronics bottle. Common frequencies in these units range from about 300 kHz to 600 kHz and above. Again, the tradeoff between the higher resolution of the high frequency and the longer range of the low frequency comes into play.

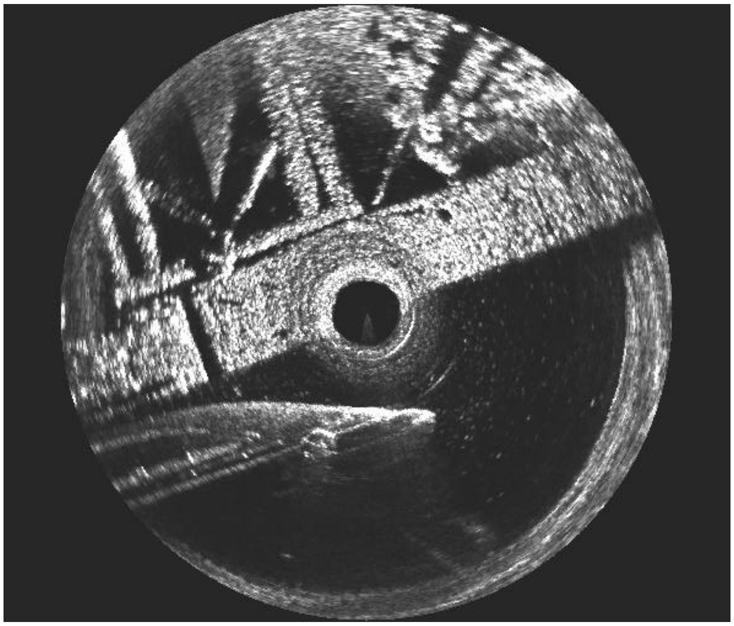
MS 900 Scanning Sonar (Kongsberg Simrad)

SM 2000 Multibeam Sonar (Kongsberg Simrad)

A vehicle may have more than one rotary scan sonar mounted on it. Two frequencies on two sonar heads working simultaneously, for example, will give a pilot a rapid informational update for targets and terrain on both high resolution and long range. A common use of scanning sonar is to mount it on a stable platform independent of the vehicle. If the vehicle has a sonar target on it, a navigator can vector the vehicle pilot to specific targets for investigation. An advantage of this configuration is that the pilot does not have to stop the vehicle to stabilize the sonar head. Another is that the sonar head can be mounted higher in the water, thus providing optimal grazing angles and backscatter. In either case, the rotary scan sonar is an indispensable tool for the vehicle operator. Several examples of scanning sonar applications follow.

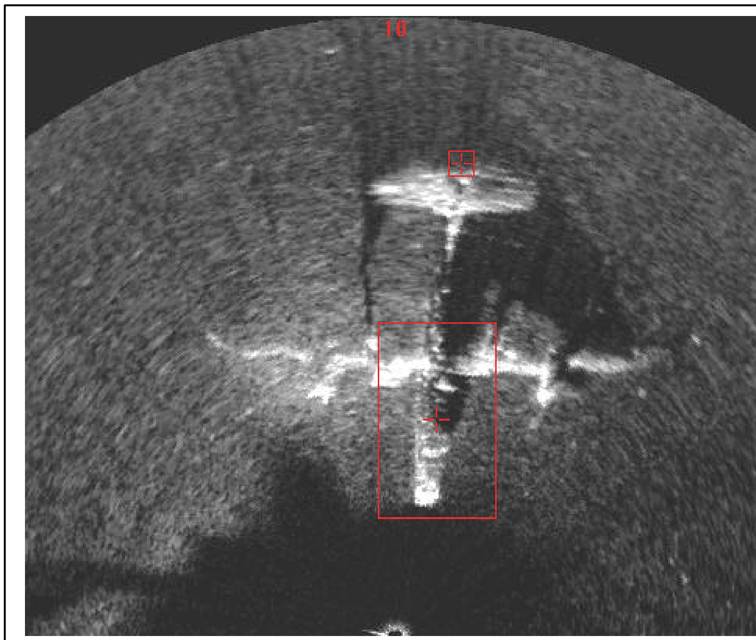


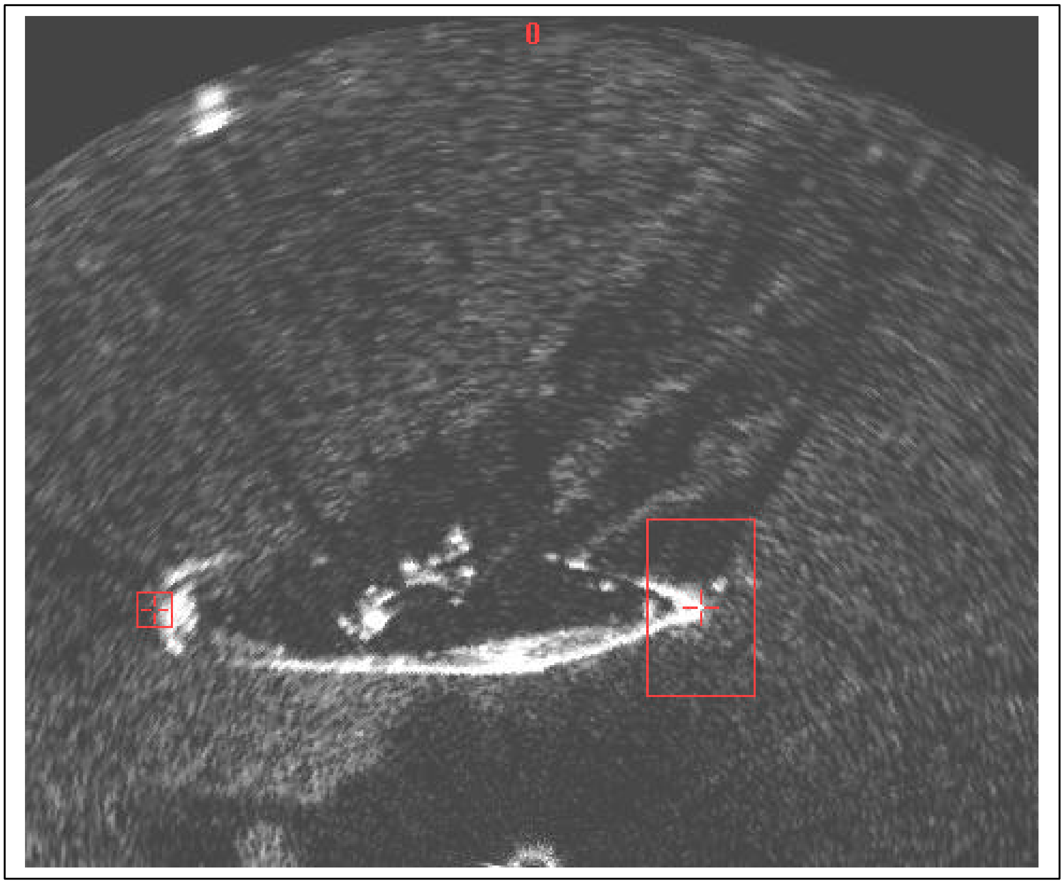
In the image above, made with a scanning sonar, a shipwreck is visible about 49 ft (15 m) from the sonar head. The total range displayed is 98 ft (30 m). Behind the sonar (in the lower part of the screen) a variety of rock outcropping can be seen. The red rectangles are zooming and target utilities used by the sonar processing software.



In the image to the left, from a scanning sonar, the maximum range is 10 meters. The sonar head was mounted below and to the side of a dock. The targets in the region consist of a dock and its support structures. The resolution in this polar plot is about 4 centimeters. The major structure running from left to right is the main body of the dock and the targets running at an angle to this are the cross member supports.

In this scanning sonar image of an aircraft, the sonar head was directly in front of the plane's nose. The maximum range setting was 40 meters. This aircraft is a commonly insonified target and this image can be compared with the side scan image shown of the plane at the beginning of this section. Although the side scan may seem to be more definitive, the scanning sonar has the advantage of continually imaging the target from a singular position. Side scan must be physically moved past the target.

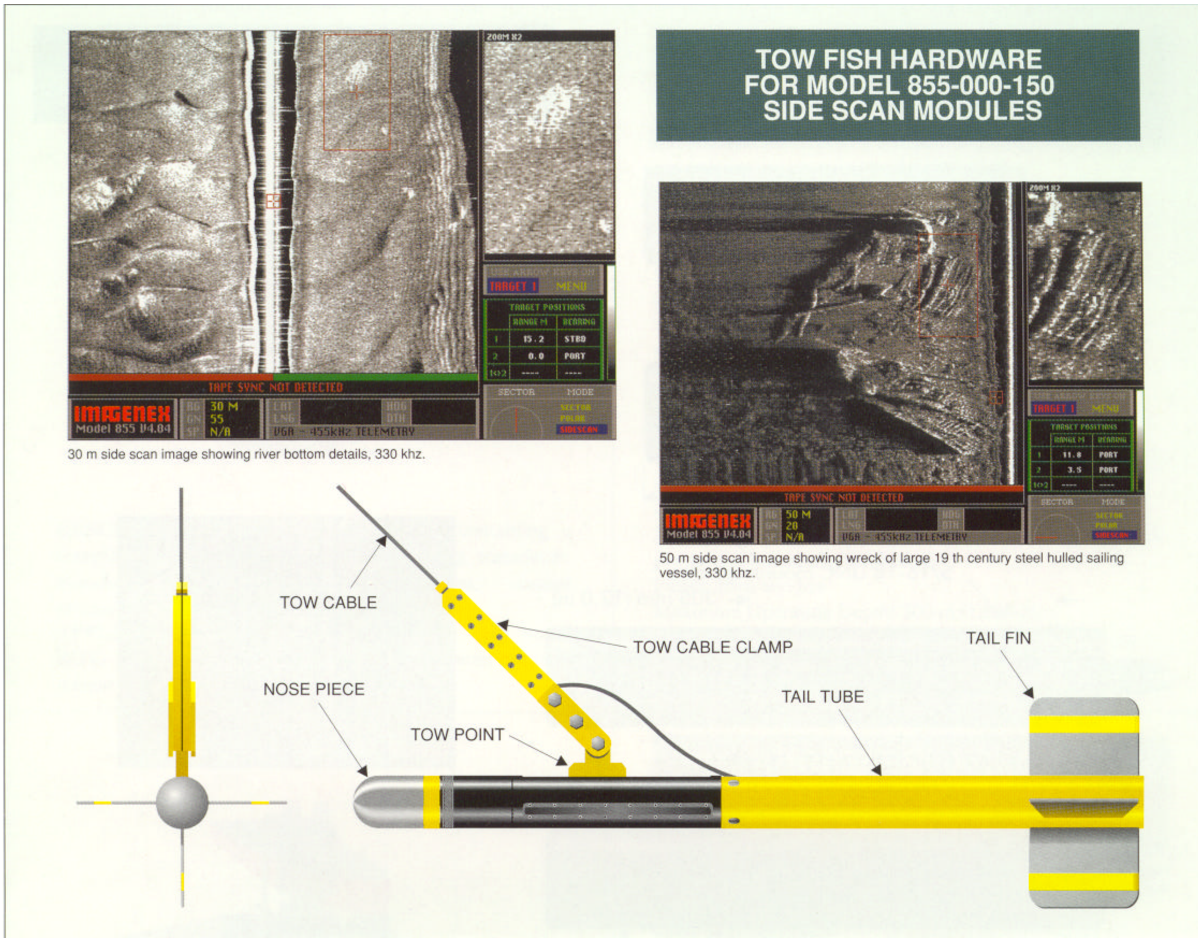




In the scanning sonar image above, a sailboat is imaged at a 98 ft (30 m) maximum range. Complexities on deck are clearly shown and in the "shadow" of the vessel it can be seen that the sails are still rigged. This is evident by the darker area beyond the actual hull returns.

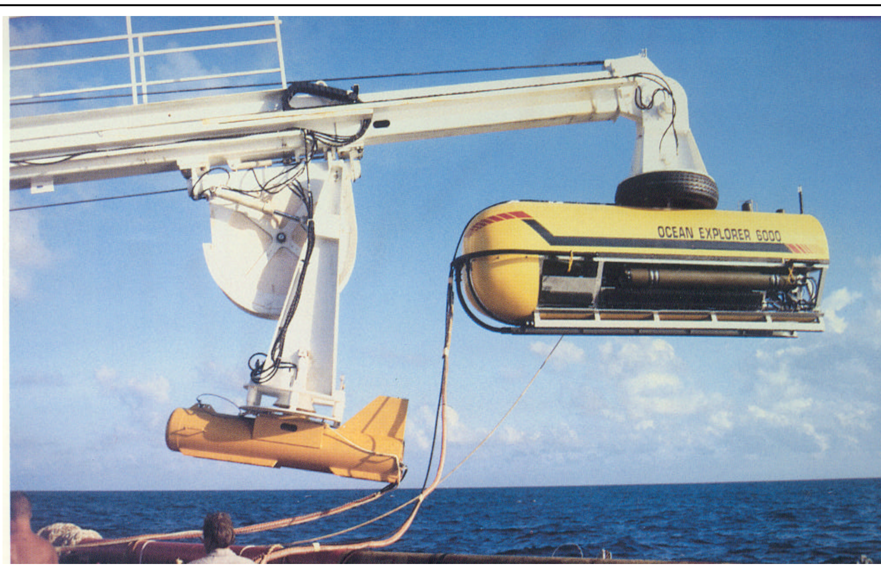
Sonar System Components

The components of an imaging sonar system include a sonar "head," or "towfish," which contains the transducer assemblies, a cable or umbilical, a display/control unit and data storage and/or printing modules (see earlier figure). The transducer assembly is the underwater or "wet" portion of the system. In the case of linear sonar such as side scan, this is mounted on an AUV/ROV vehicle to provide the movement needed to scan the environment. In the case of rotary sonar, the movement is provided by the sonar head, which is motorized to turn the transducer assembly mechanically. Examples of two towed search sonars, which range from Imagenex Technology Corporation's small Towfish to Oceaneering's full ocean depth *Ocean Explorer 6000*, are provided in the following figures.



Above:

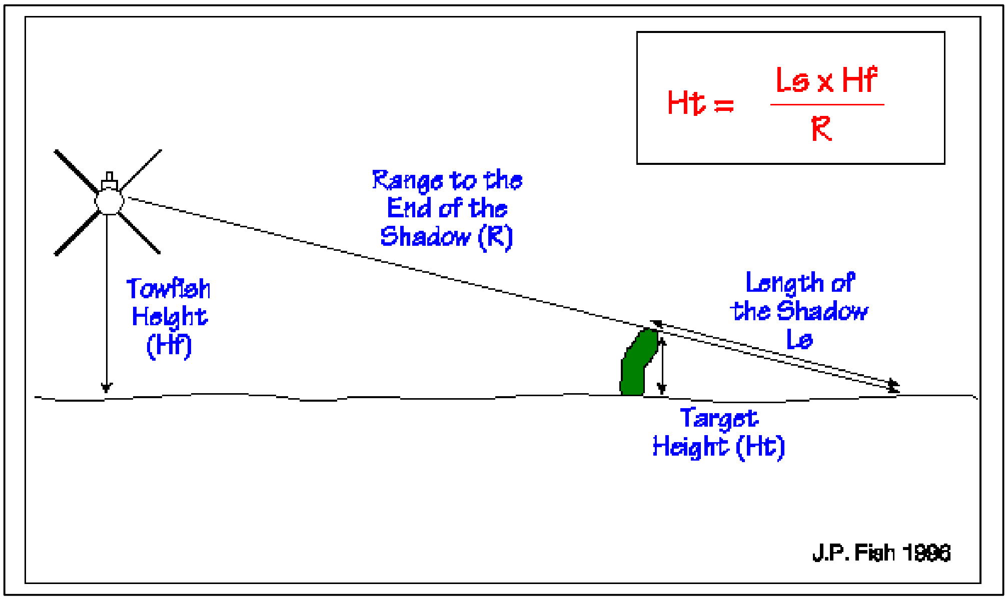
Imagenex side scan sonar

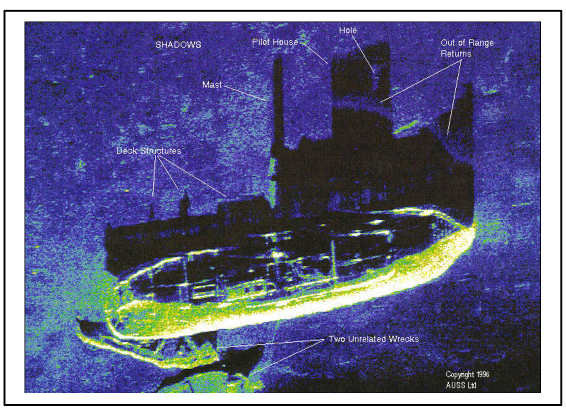


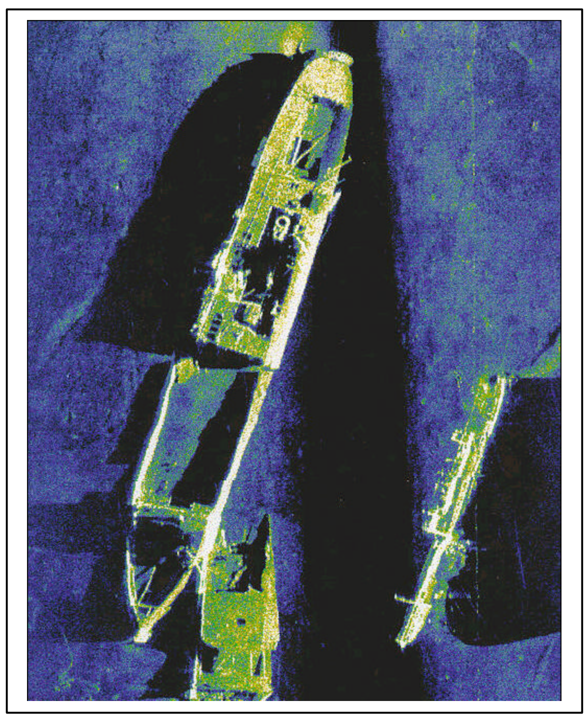
Right:

Oceaneering's *Ocean Explorer 6000*

The fact that towed side scan sonars "fly" high above their targets gives them their ability to observe objects, often through the "shadows" cast by the sonar beam. This is shown graphically in the following figure and also in the two ship images.

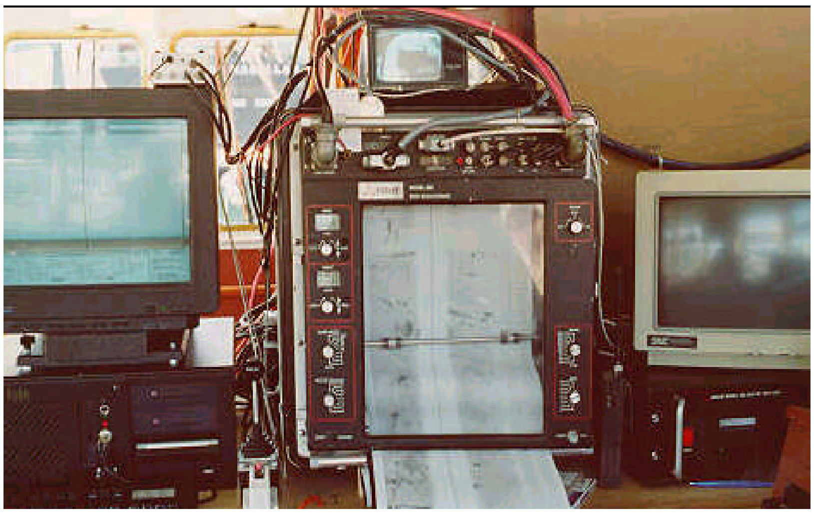






Sonar displays.

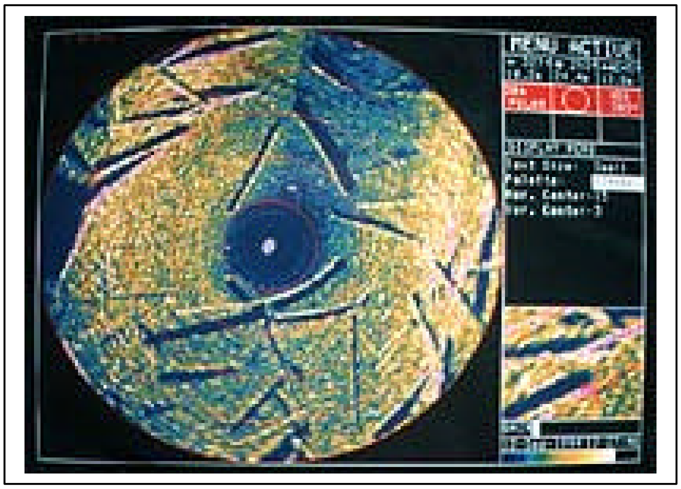
Early linear sonar displays were hard copy printers, which relied on the existing technology of the 1940s and 50s. These were a series of "graphic recorders". The early designs used a wet, conductive data recording paper to print the image. Some of the minor short-comings of the wet paper printers were that they required a fairly high level of routine maintenance, the resulting record was not dimensionally stable and it was susceptible to fading from exposure to UV light. In the late 1970s a dry electro-static printer paper came into use and is still widely used today in several kinds of scientific data recorders. In the late 1980s thermal paper and film recorders were produced that eliminated the odor and the smudging problems associated with electrostatically printed records. Printing was a one step process where a line of heaters in contact with the paper created the image.



Modern developments in sonar displays allow the user to view data on a color CRT. However, the CRT display is available in different types and formats. Some sonar systems send data to a composite video monitor in the form of RS-170 video format. Other systems use RGB monitors. While both types of displays are capable of color, there are tradeoffs between the two.

While the video format can conveniently be stored on video tape and later redisplayed on a common VCR, the resolution and color quality of the video display is fairly low even before data storage. In composite video monitors the phosphor decay rate is slow and does not allow for rapid screen refresh rates, further reducing image clarity. Although the resolution of the video format may improve, such as with the use of Y-C composite, great leaps in increased resolution are not expected.

RGB monitors, on the other hand, provide a display that gives the operator a significantly better image of the data in terms of both resolution and color rendition. Whereas older RGB monitors have a display resolution of 640x480 pixels with 16 colors, high-resolution monitors have greater capabilities.



Underwater logging viewed by the SM 900 scanning sonar (left) (Kongsberg Simrad)

Display cards and CRT monitors are available that can display more than one thousand vertical and horizontal pixels and millions of color triplets. Further, most modern displays also have a fast refresh rate, which reduces eye fatigue for the operator.

Data storage and redisplay of sonar information is somewhat more cumbersome than with video. Data from many sonar systems that use RGB displays is digitized and can result in substantial amounts of data. This data is stored on magnetic or optical storage media and is usually only redisplayed through the sonar system or a computer.

Modern Digital Sonar Systems

One of the most significant advances in sonar technology has been the application of digital processing to sonar data. Early sonar systems received their reflections, amplified and transmitted them in analog form up the umbilical for display. These older analog systems had a variety of limitations. The analog signal degraded over long cables, resulting data was cumbersome to store and difficult to manipulate in post processing.

Originally, manufacturers designed digital sonar to allow a simple method of distortion correction. Recently however, sonar processors have become available that go far beyond error correction and give the user high resolution and a variety of post-processing capabilities. In display appearance many digital systems provide data similar to the older systems. The major difference is they are very immune to noise and allow numerous ways of manipulating and reviewing data. The increased resolution of these new systems provides a data density that is much higher than can be displayed on the CRT. By using computer memory, specific sections of the sonar data can be enlarged for closer examination. By enlarging a section of a record, the CRT is able to display the full resolution of the data. Most modern imaging sonar systems are digital and have digital signal processing (DSP) capabilities. Some have optional interfaces such as a SCSI port to connect to digital storage media and full resolution VGA displays as well as display and record NTSC and PAL video in real time.

Data for post processing can also be gathered by AUVs. Side scan sonar adapted to special software is currently being fitted to AUVs. Sonar data acquisition software allows the gathering and mass storage of side scan data from the AUV which uploads the data upon vehicle retrieval, or the data can be transmitted acoustically to the surface as in the Advanced Unmanned Search System discussed elsewhere in this publication.

The Future

Although limited by the basic physics of sound in the underwater environment, engineers will continue to improve the extension of our vision through sonar. Future developments are likely to include improvements in beam patterns and resolving power for any given frequencies. DSP technology and developments in digital enhancement of data will continue into the next century. Beam steering through phased array transducer assemblies will continue to be developed and miniaturized as will materials used in transducer construction.

One sonar design very popular in the 1960s and 70s was the CTFM (continuous tone, frequency modulation). This design is re-emerging as we move into the next century. Because this type of sonar emits a continuous tone rather than individual pings, the sweep rate is less dependant upon the range setting of the display. Sweep rates on the order of 30 degrees per second and an audio feature, which varies frequency with returned sonar energy, give the ROV pilot information he can both see and hear.

Eventually, the long-range goal of combining optical and acoustic data in one display, thus gaining the most information in a single image may be met. There are difficulties in this however because optical information, although possessing very high resolution, is severely limited in range and long range sonar data has the opposite problem.

It is conceivable that the vehicle of the 21st century will have a multitude of miniaturized acoustic sensors mounted on its circumference. In such a manner, the entire periphery of the work area can be insonified or probed at the same time. This will provide a continuous view for the pilot completely around the vehicle beyond the range of camera and lights.

For more information on imaging sonar such as side scan sonar please see Sound Underwater Images by Fish & Carr, Lower Cape Publishing, Orleans, MA USA

Manipulators

The Requirement for Manipulators

Because the underwater environment is intrinsically inhospitable to humans, using remotely manipulated mechanical arms is a natural way to perform subsea work. Remote manipulation (also called teleoperation) allows human operators working from the surface to manipulate underwater objects. A teleoperated manipulator is not the same as a factory robot that repetitively performs a single assigned task or set of tasks under controlled conditions in a structured environment. Instead, a telerobotic manipulator is the mechanical equivalent of human arms and hands. It manipulates objects under direct human control in real time (that is, while the task is being performed) and can therefore function in an unstructured environment. The most basic remote manipulator systems contain only an operator-input device and a jointed manipulator arm. More sophisticated systems also contain control electronics. The tip of the manipulator arm is attached to a tool (such as a pair of jaws, a drill, or a pair of snips) used to perform the required task.

Before remote manipulators were developed, divers were required for all subsea operations. Divers are still able to perform some subsea manipulation tasks, and they have the advantage of human dexterity. Remote manipulators, on the other hand, can go into deeper water, can have superhuman strength, and do not have the legal liabilities associated with using human workers for dangerous tasks.

Manipulator and Controller Types and Applications

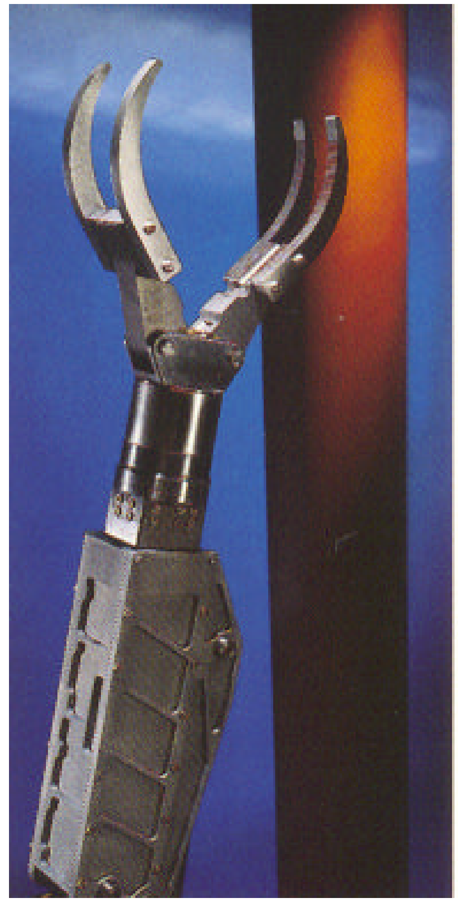
Manipulator Types

A wide variety of manipulator types have evolved to cover a very broad range of subsea applications. These applications range from simple tasks, such as grasping a lift line, to more complex ones, such as plugging and unplugging electrical and hydraulic connectors. When selecting a manipulator, it is important to choose the simplest possible type that can accomplish the task in a reasonable time. In the offshore environment, complexity can generate problems with reliability, operation, and maintenance.

<u>*Grabber Arms*</u>

Grabber arms are the simplest forms of manipulator arms currently in use. They are typically characterized by very few degrees of freedom (some have only one), but may have as many as seven. Grabber arms are very robust in construction, and generally rely on vehicle motion for final gripper positioning. This type of arm can be used by itself for very simple manipulation. It can also be used to hold a vehicle or ROV on station by grabbing part of the work site while a more dexterous arm performs manipulation tasks.

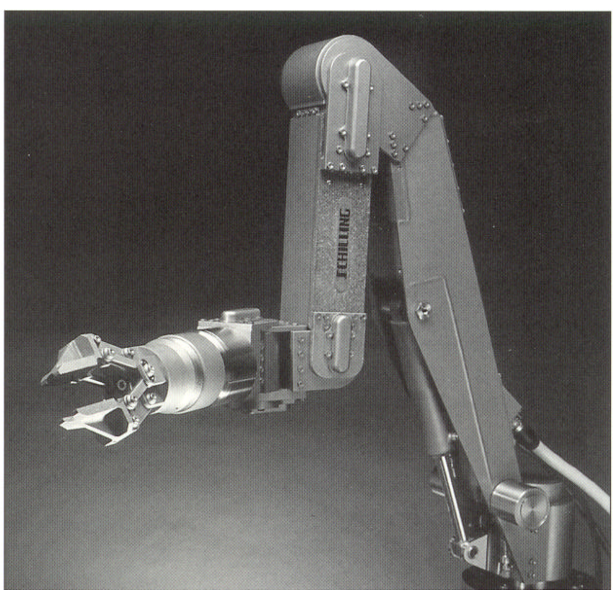
Grabber arms vary considerably in type and size, from simple one-function, electrically actuated systems for very small vehicles up to seven-function, hydraulically powered systems for larger ROVs. The most broadly used type of grabber is a five-function arm, usually equipped with very large gripper jaws that can easily grasp large objects at the work site to hold the ROV in position (see figure).



RigMaster five function grabber (right)

Dexterous Arms

Dexterous arms usually have more joints or degrees of freedom than grabber arms. The minimum number of joints generally used for a dexterous arm is six, plus the tool or gripper function. It is advantageous for dexterous arms to be more slender and cleaner on the outside than a grabber arm, which facilitates access to confined work areas. The use of six joints or degrees of freedom in addition to a very compact wrist allows the operator to position the tool or gripper arbitrarily within the arm's workspace. This is important since if the arm is not sufficiently dexterous, it can be very difficult to access locations that can be easily seen through the camera; in such a case, the operator can see his objective, but the arm can not be physically positioned to allow task completion.



Titan III dexterous arm (left)

The most popular type of dexterous arm is the backhoe or elbow-up design (see left figure). This design is different than the anthropomorphic or human-like design. The backhoe design has become popular primarily because it represents a good compromise between desirable operating characteristics for the arm and compact storage on the ROV.

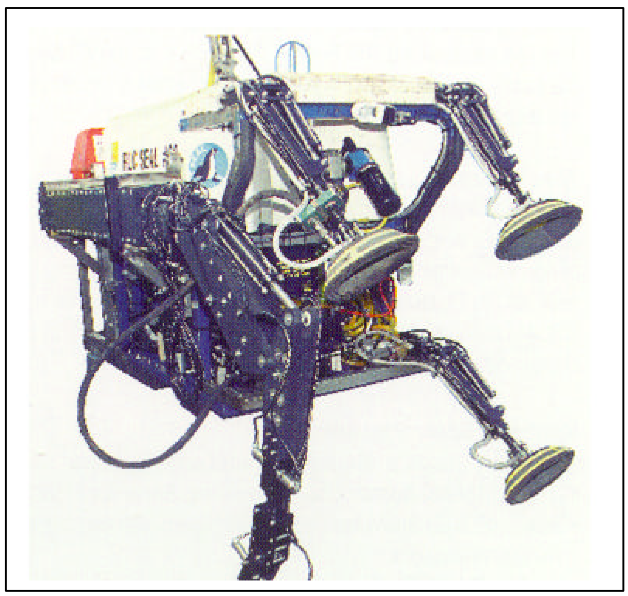
Dexterous arms usually have a wrist rotate function that allows continuous gripper rotation. This feature is valuable for tasks like valve actuation, shackle makeup, or screw clamping. Continuous rotation allows the operator to make multiple turns of the gripper or tool without letting go of and regrasping the object.

Dexterous arms also are typically equipped with more sophisticated control functions. These functions allow the operator to make more complex motions with the tool, including the ability to make straight-line motions or to move along paths that require all arm functions to be actuated at the same time. The combination of the arm's dexterity and more sophisticated control types allow the operator to perform tasks such as following surfaces or inserting electrical or hydraulic connectors.

Suction Arms

Suction arms are a specialized form of grabber used to steady the ROV, allowing operators to use more precise tools such as dexterous manipulators or measuring instruments. Suction arms are typically very simple, having only two or three degrees of freedom that can be passively or actively positioned (see figure). The passive types require the use of the ROV or dexterous manipulator to position the suction arm. Once the suction arm is in position, a water pump is turned on. This creates suction that pulls a large rubber cup at the tip of the arm into contact with the work site.

RACAL *Seal* ROV with suction cups attached to positioning arms (below)



On models that use passive actuation, this suction force also locks the arm's joints in place. The primary advantage of this type of device is the ability to stabilize on surfaces that are too large or do not have features that allow the use of a typical gripper. The chief disadvantage of this type of system, like any specialized device, is that it cannot be easily used for other purposes.

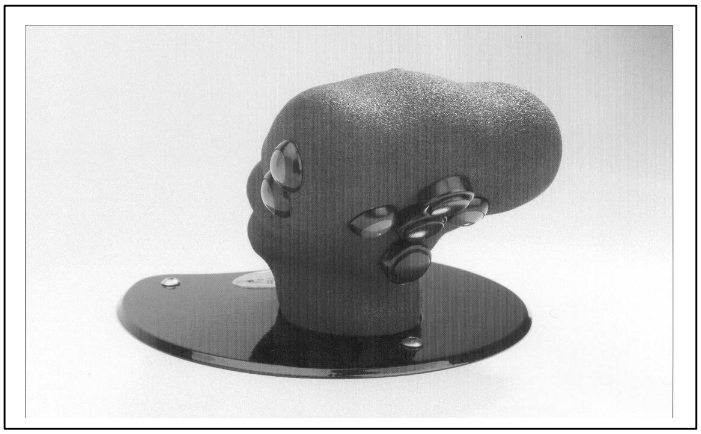
XYZ Tool Deployment Units

The XYZ tool deployment unit is another type of specialized manipulator. The XYZ tool excels in applications where tasks are arranged in a matrix, such as a linear array of valves. (This situation occurs regularly on subsea valve panels.) The system is designed to move a tool (usually a torque tool) along three linear axes. By eliminating the additional degrees of freedom on a typical dexterous manipulator, the operator does not need to be concerned about the additional orientation axis and can much more easily align the tool with the task. This saves time and can reduce equipment damage. The chief constraint of the XYZ tool deployment unit is that it cannot be used for other routine manipulation tasks because of its limited degrees of freedom.

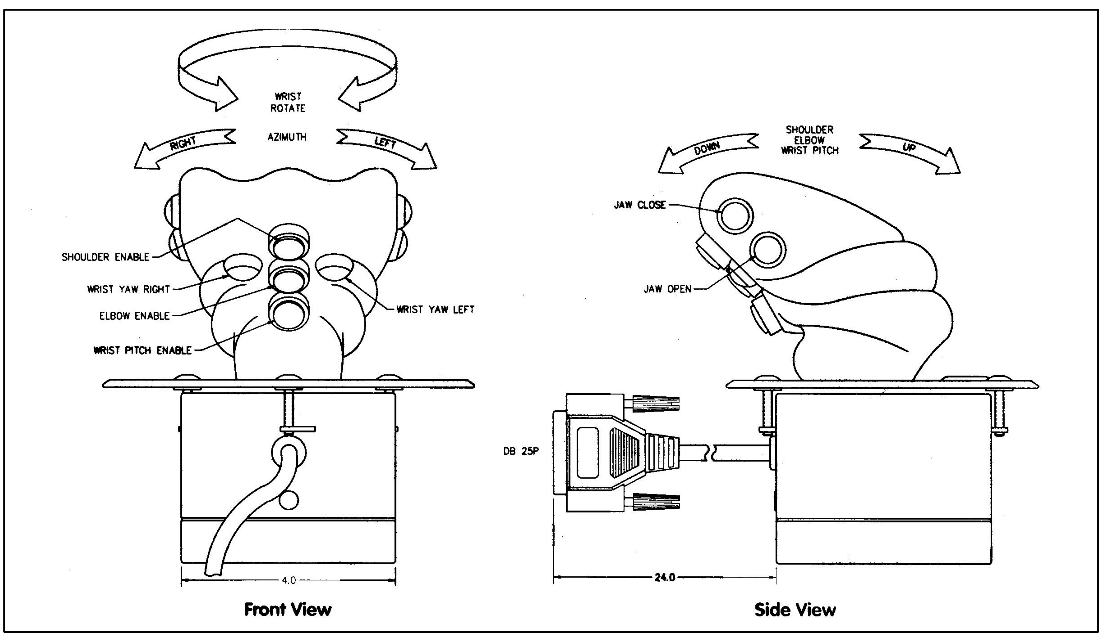
Control Types

<u>On/Off Control</u>

On/off control (also called rate control) is the simplest form of manipulator control. In rate control, the operator directly applies hydraulic power to individual manipulator functions through a manifold of manually operated servo valves or electrically operated solenoid valves. A given function moves when its valve is open and stops when the valve is closed. Typically, only one function is operated at a time. The operator input device typically consists of a joystick, with one switch for each function (see figures).



On/Off input device



Rate control has the advantage of being economical and robust, but precise and fluid manipulator movement is difficult to achieve.

Spatially Correspondent Control

Master arm

Spatially correspondent control (also called position control) uses a small replica of the manipulator arm (called the master arm) for operation (see figure). Each manipulator arm joint or function has a kinematic analog in the master arm. As the operator moves the master arm's joints, the manipulator arm almost instantaneously reacts with corresponding movements. The operator observes the arm's response, and makes movement corrections accordingly. Using a replica master arm makes operation of the manipulator arm simple and intuitive, and the simultaneous movement of multiple joints results in precise and fluid manipulator movements.

Position control is much more sophisticated than rate control, and is correspondingly more expensive. Position control requires the following additional elements:

- An electrical power source
- A replica master arm
- Position sensors at master arm and manipulator arm functions
- Control electronics to process signals going to and from the master arm, manipulator arm, and hydraulic valves.
- Electrical cables connecting all system electrical components.

For a position-controlled manipulator, the control system operates by simultaneously gathering data from sensors in the slave arm and master arm, processing system data, and outputting information required to make all system components function. When the operator moves the master arm, position sensors in the master arm send signals to the control electronics about the position of master arm joints. At the same time, the control system is gathering data from slave arm position sensors about the position of slave arm joints. The control system then compares master arm and slave arm position data. If the master arm and slave arm positions are not the same, the slave controller sends signals to appropriate hydraulic valves, resulting in the release of hydraulic fluid to selected slave arm actuators. This drives slave arm joints into correspondence with master arm joints.

Position-controlled manipulator systems may also allow commands to be input through keypads or pendants. This lets the operator affect the manipulator arm by issuing commands for preprogrammed slave arm movements, such as a series of movements to stow or deploy the manipulator arm. The system may also be programmed to detect certain system error conditions and to automatically shut down hydraulic power when the errors occur. Some systems can display information on master arm and manipulator arm positions and conditions for diagnostic use.

Force Feedback Control

Force feedback (also called bilateral control) provides the operator with information about the forces between the tool and the work. In a typical system, these forces are measured at various points on the arm and transmitted back to the operator's control unit. This force information is used to apply a representation of the force to the operator through a motorized version of the replica hand controller. This information provides the operator with tactile feedback in addition to the normal video feedback.

Force feedback arms are the most complex and costly arms available because the system requires two active or powered robots instead of one.

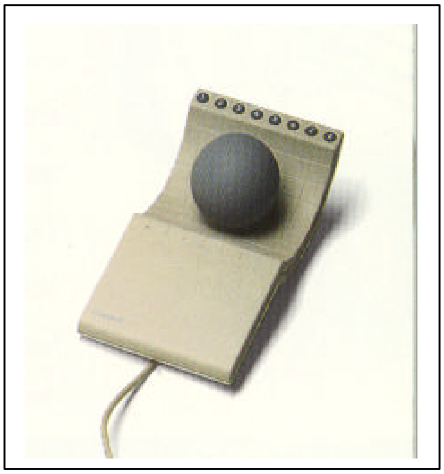
Robotic Control

Robotic control refers to functions that can be performed automatically. The most common use of robotic control is an automatic or pre-programmed stow sequence for the arm. This relieves the operator of the burden of manually moving the arm into the correct position when it is not going to be used. Robotic control can also be used to retrieve tools from storage locations.

Robotic control has not yet become popular because it requires that the operation be pre-planned. At present, very few operations lend themselves to pre-planning of the arm's motions.

Resolved Motion Control

Resolved motion control translates an operator's commands into straight-line motion, much like the XYZ tool deployment unit. However, in resolved motion control, this is accomplished in software rather than by the mechanical design of the system. An arm with resolved motion control can perform a wide variety of tasks under standard control, and then can perform straight-line or resolved motion when required. The input device for resolved motion control is a joystick or spaceball rather than a replica master arm (see figure next page), because the operator is actually commanding a rate or speed at which the tool should move. A joystick will return to a zero position, which stops arm motion, when pressure is released.



For effective, general-purpose operation, two types of input devices are best. The replica arm is most effective for general pick-and-play manipulation, and a joystick or spaceball works best for resolved motion tasks.

"Spaceball" resolved motion controller (left)

Performance Specifications

Depth Ratings

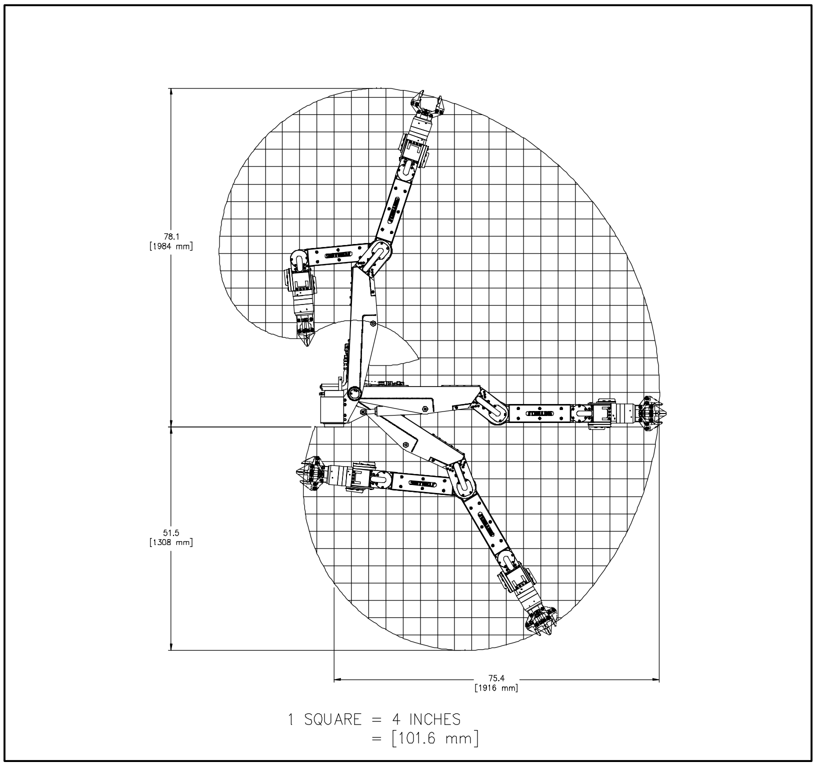
Manipulators are available with a broad range of depth capabilities. Arms are typically sensitive to depth because some parts must be filled with air to function properly. These areas typically house the control electronics or position sensors. The stresses caused by the static pressure of water depth must be limited to reasonable levels. As a result, the two types of arms typically affected by depth are electric-powered rate arms and position-controlled arms.

Because hydraulic rate arms do not contain electronics, they are not usually sensitive to depth, but they can be affected by the viscosity of their hydraulic fluid. For depths greater than 9,843 ft (3,000 m), a low-viscosity fluid must be used to prevent arm function from being impaired by fluid that becomes too thick under pressure.

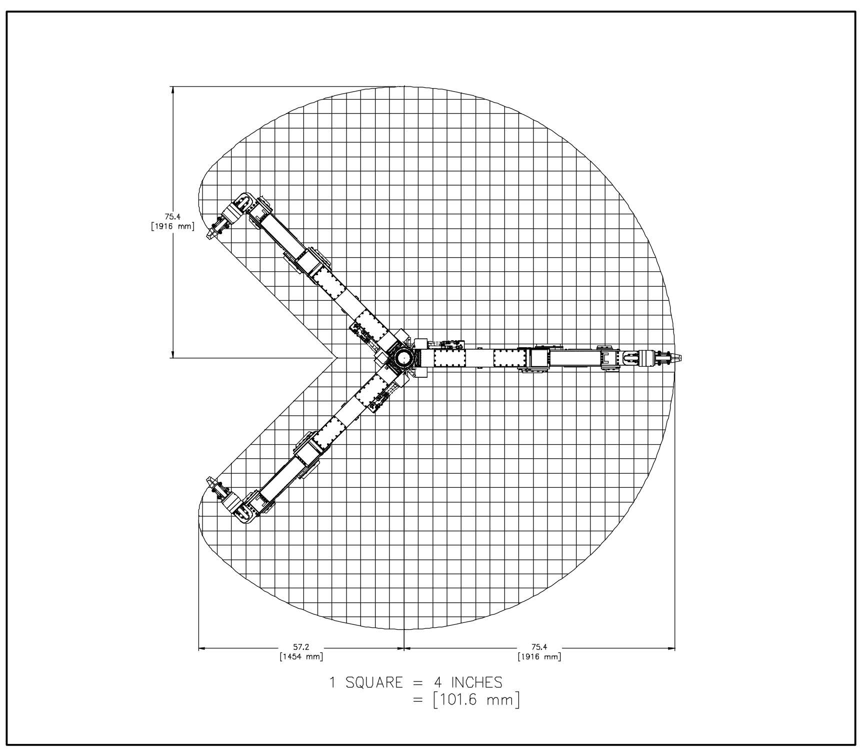
Work Volumes (Useful Envelopes)

The work volume of an arm is a complex and important characteristic. It is complex because it involves both the position *and* orientation of the tool or gripper. Manufacturers typically display the work volume with two orthogonal views of the arm's joint range (see figures next page). This is the best way to represent joint range, but does not tell the user if a specific task can be performed.

If the user needs to perform a complex task, the best evaluation technique is to model the arm's motion on a computer or to mock up the test in a shop trial. To model the task, a set of CAD files can be requested from the manufacturer.



Dexterous arm work envelope – side view



Dexterous arm work envelope – top view

Lift Capacities and Lift-to-Weight Ratios

Most manipulators are rated for the maximum stall force at maximum extension, and this rating provides a reasonably good idea of the machine's overall capacity. For designs that are less capable in other area of the work volume, the manufacturer should list the capacity at worst mechanical advantage.

The lift-to-weight ratio of an arm is a measure of lifting efficiency. Excess weight is always an issue on remote vehicles, and good lift-to-weight performance helps to reduce system weight. When selecting a lift capacity, it is important to consider what kind of overturning forces the vehicle can tolerate; otherwise, the system will be equipped with capacity and weight that provides no benefit.

Operational Requirements

Hydraulic versus Electrical Power

The smallest manipulators designed for use on small observation ROVs are electrically powered, while the rest of the manipulator systems used on ROVs require hydraulic power. The sharp distinction between the two classes of systems is for purely practical reasons. Larger systems require hydraulic actuators to achieve acceptable power levels in reasonably sized packages, while smaller observation ROVs are all electric. The use of hydraulic power allows the manipulator to deliver large forces and to be capable of withstanding severe impact loads. Also, the power source or HPU can be located away from the arm, improving ROV weight and balance.

In the near future, advances in magnetic materials will begin to allow the design of larger electric manipulators. Electric manipulators have greater power efficiency compared to hydraulic systems because of the inherent inefficiency in converting electric to hydraulic power at the HPU. For the present, however, very small arms will be electric and larger arms will be hydraulic.

Hydraulic Requirements

Most manipulators are designed to operate at 3000 psi (200 bar). While this nominal operating pressure is preferred, systems can be operated on lower pressures with reduced performance. Operation at pressures below 60 percent of the design pressure becomes impractical due to excessive performance loss.

Typical hydraulic fluids are mineral based with a viscosity of 15-40 centistoke, but systems are increasingly being designed to work with water glycol fluids. The manufacturer's data for each arm should be consulted for specific fluid compatibility.

Flow requirements are also stated in the manufacturer's literature. The faster the arm moves, the greater the required flow. Most arms will operate satisfactorily at 30 to 40 percent of the maximum stated flow. Use on ROVs with flows below this level this will cause the supply pressure to drop dramatically during arm motions, and is not recommended.

Arm manufacturers offer accessories that tailor systems to specific tasks. Hydraulic accessories can be operated in conjunction with the arm by adding control manifolds connected to the arm's control system. This allows tools like torque wrenches or wire brushes to be controlled by the manipulator operator.

An auxiliary input device such as a spaceball can be added to provide straight-line motion for tasks such as inserting hydraulic hot stabs or connectors.

Force/torque sensors are available from some manufacturers. They allow all forces that act on the system's tool to be output to other control systems. This feature can be valuable for sophisticated control techniques such as surface following.

Three dimensional (3D) visualization and control systems are also available to provide the operator with information about arm position to supplement the view available through the video system. This information is helpful when the work site has limited visibility.

Manipulator Tools

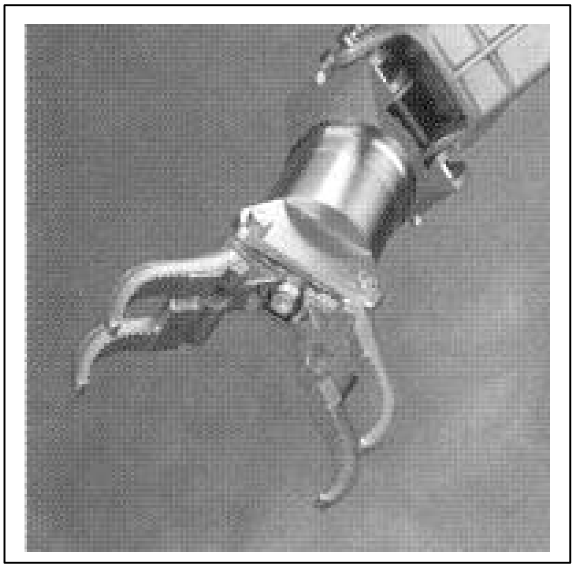
At the tip of all manipulator arms is an end effector (or tool) that is used to perform the manipulation task. For subsea applications, tools are generally hydraulically powered. The most common tool is a gripper.

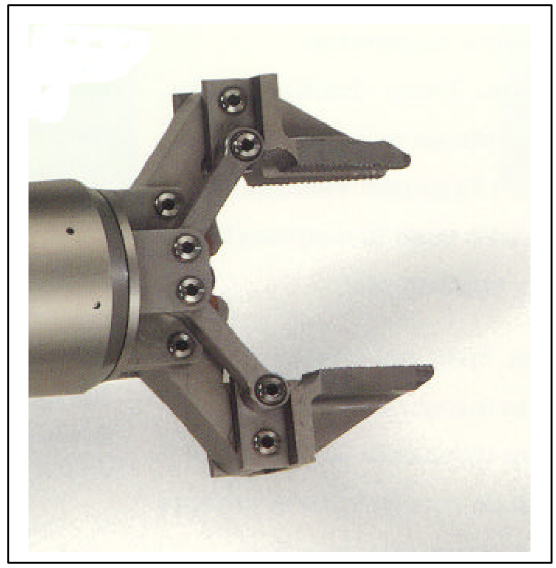
Grippers

Grippers are tools that can grasp objects by closing around them. The gripper can be used to perform a variety of tasks: to pick up an object for transport, to stabilize the ROV (for example, by gripping a pipe on a platform to anchor the ROV next to the platform), to manipulate equipment in the same way a human would (for example, to turn nuts and flip latches), and to pick up other tools (such as a scoop used to pick up soil samples). Gripper elements may be smooth, or may be notched to keep the grasped element from slipping out.

Grippers come in many configurations. Grippers with tines (also called fingers) are used to grasp cylindrical objects like pipes (see figure next page). Such grippers typically have two, three, or four fingers.

With parallel-acting grippers, the gripping surfaces remain parallel to each other as the gripper opens or closes (see figure next page). Such grippers are useful for grasping almost any object.





Conan's intermeshing gripper **Parallel-acting gripper**

Information on gripper force is available in the manufacturer's performance specifications.

Some grippers are capable of being in only two states, completely open or completely closed. This characteristic makes grasped objects vulnerable to crushing. Other grippers are capable of incremental movement (that is, movement of the gripper elements can be stopped when the gripper is partially closed.) The combination of incremental gripper movement and force feedback (described in the section on manipulator control systems) can prevent the operator from damaging delicate items.

Other Tools

Tools other than grippers are available either as standard products or custom designed items for special tasks. These tools includes drills, snips for cutting through light materials, cable cutters for slicing through rope or conduits, and wire brushes for cleaning or abrading surfaces (see figure - right).

State of the Art

The most popular manipulator systems used today provide a combination of critical characteristics: good dexterity, ruggedness, and ease of maintenance. The typical ROV is fitted with both a grabber arm and a dexterous arm. The two most popular grabber arm types are a five-function arm with a prismatic or linear extend capability and a seven-function, backhoe-style arm. The most important features to look for in a grabber are gripping capacity and ruggedness. Because these arms see a great deal of abuse in operation, they should be robust in construction with large-diameter bearings at all pivot pins and large-diameter actuator rods. Models with bearings and rods that are smaller than 0.75 inches (1.9 cm) are subject to frequent breakage.

The dexterous arm should have a short wrist length for access to confined spaces, since long wrists prevent the operator from reaching many areas within the required envelopes. Dexterous arms should also use a small master arm to prevent operator fatigue. Master arms that are longer than 18 inches (46 cm) can greatly increase fatigue and reduce productivity.

Most modern arms employ modular construction, which can shorten repair time and reduce service cost. Modular construction is characterized by actuators that can be readily removed as entire units and that have multiple uses throughout the arm.

Future of Remote Manipulation

Standard Architecture

Adopting a standard architecture for ROV signals, electrical power, and hydraulic power will allow both the rapid integration of manipulators into vehicle systems and easy sharing of manipulators between vehicles. Also, reducing the number of electrical connections required between the manipulator and the ROV will increase reliability.

Robust Interchangeable Tooling

ROVs are typically retrieved after a task is completed so that they can be reconfigured with tools and materials required for the next task. Providing the ability for a manipulator to exchange tools at the sea floor work site would allow a manipulator to perform a variety of tasks during a single dive, greatly reducing operation costs. This interchangeable tool facility must be efficient and reliable, must provide suitable power, and must resist contamination from sea water and silt. Tool interchange is another area where pre-programmed routines can apply.

Force-Compliant Control

Many remote intervention tasks performed by manipulators involve handling sensitive or fragile components such as electrical connectors and valve stems. Force-feedback in manipulator systems will increase the chance that such components can be handled without harm. Force-feedback systems have existed since the 1960s, but they are costly and have generally suffered from poor reliability.

A cost-effective alternative is to perform routine operations by controlling forces at the servo level. This approach has the potential to eliminate the operator from the force loop, eliminate the force-feedback hand controller, and limit overloads and potential damage.

Systems Engineering

Current subsea operations use remote manipulators in systems and situations that were designed with no provision for remote intervention. Such work is inherently costly and difficult to perform because machines are used to perform tasks that were developed with human anatomy and dexterity in mind. For example, integrating and fielding technologies for ROV manipulator-based oil platform node weld inspection have been slow because requirements for robotic inspection were not considered when the platform node was designed.

Today we are approaching the practical limitations of telemanipulation, given current work site designs and the increasing complexity of sea floor equipment. The next major technological advancements in remote manipulation will focus on modifying the work site interface to produce dedicated tooling interfaces that are designed to work with remotely operated equipment, such as the valve stems designed to accept torque tools. Remote intervention can be most effectively applied when it is considered in the early phases of systems engineering. This practice (called co-design) greatly increases the chance of successfully applying remote intervention techniques to sea floor equipment problems, since ROV interfaces, manipulator work envelopes, and work site layout can all be considered simultaneously and designed to make task performance simple and efficient.

Model-Based Robotic Control

A teleoperated manipulator performs tasks under direct human control in real time and can function in an unstructured environment. In contrast, a robotic manipulator (or robot) automatically performs pre-planned tasks. As subsea work sites are redesigned for remote manipulation, they can also benefit from manipulator systems that work under robotic control.

The robots used in subsea applications will not be like factory floor robots that repetitively perform single tasks. Instead, these robots will be part of sophisticated systems that allow operators to display a detailed “virtual reality” model of the work site and the robot arm on a computer screen. Such systems will be designed for work that requires the operator to plan a manipulation task, preview and fine-tune that task using the manipulator model on the computer screen, and then automatically execute the operation with the real manipulator arm.

To use a model-based manipulator system, the operator first creates a detailed virtual model of the manipulator’s work site on a computer screen. Once a simulated manipulator arm is incorporated into the model, the operator can easily simulate complex and precise manipulator movement trajectories and observe their effects on objects in the work site. By previewing a process on the computer screen, the operator can study simulated manipulator motions from different views and with different parameters to determine which motions produce optimal results. A collision-free path planner could automatically plan paths around obstacles and ensure that the tool on the manipulator arm always reached the correct location in the desired orientation. Once the optimal movement path had been planned, the operator could automatically execute that path.

This computer-aided teleoperation offers features that greatly enhance task performance over standard operator-in-the-loop teleoperation. These features include automatically detecting potential collisions, moving the slave arm directly to an object or along a pre-defined curve, and recording manipulator movement paths for later review or playback.

Model-based control also provides almost infinite possibilities for viewing a task or work site. The operator can establish any number of “virtual cameras” in the work site model and simultaneously display multiple views on the screen. The operator can view objects from any camera location or angle, pan around them, and zoom in and out. By creating a viewing site at the end of the slave arm, the operator can even get a “tool’s-eye view” of the task being performed. (See the section on training for an example of such models).

Model-based control will become even more powerful when subsea work sites are designed for ease of remote intervention, because routine tasks will lend themselves more easily to the performance of pre-programmed tasks.

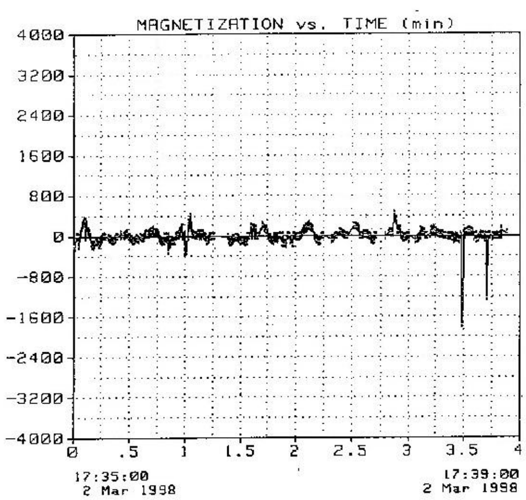
Sensors – Surveying Small Diameter Subsea Cables Passively

Existing technologies for surveying small diameter subsea cables are severely limited in capability; however, Innovatum Inc. is developing the technology that will provide a solution. Innovatum has discovered a way to greatly increase the potential tracking range for even the smallest cables by using artificial magnetization. A magnetized 0.24-in (6-mm) cable can be passively surveyed from a range of over 6.6 ft (2 m).

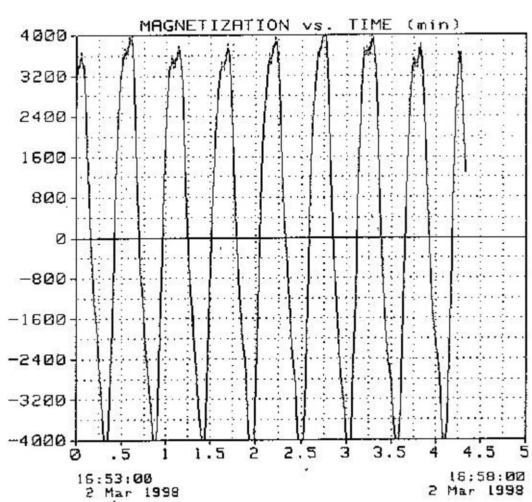
Projected worldwide expansion of subsea fiber optic cable networks will result in a greater proportion of these smaller, harder to detect cables. Requirements for protection of these cables, including the ability to rapidly locate faulty cables and verify burial depth upon repair and re-burial, must be met.

Using this new tool, the magnetization of the cable armor or strength member is significantly increased. This may be induced during manufacture, while the cable is loaded to the vessel or during the lay operation. This enhanced magnetization is permanent and in no way harmful to the cable.

Field trials of Innovatum's 1st generation cable magnetizer yielded excellent results. Two sections of 0.43 in (11 mm) diameter submarine optical cable were tracked: one magnetized using the Innovatum equipment and the other as a control. The original unmagnetized section could barely be tracked at 1.6 ft (0.5 m). The artificially magnetized cable was tracked at a full 6.6 ft (2 m) depth under the sensor array, limited only by the maximum height of the test frame. The magnetization of the 0.43 in (11 mm) unarmored cable was comparable to a 1 ft (0.3 m) diameter pipeline, with tracking and depth determination possible in excess of 13.1 ft (4 m).

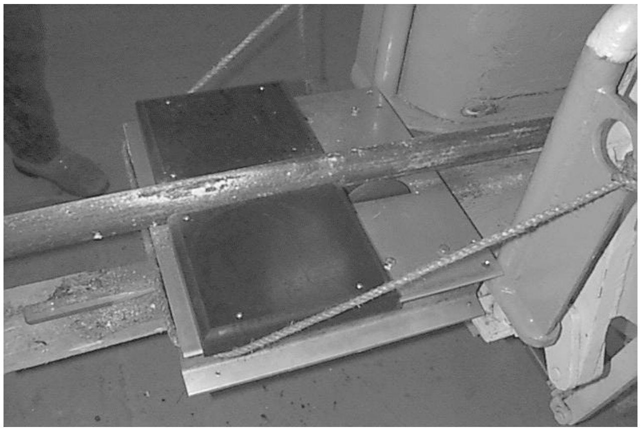


Natural magnetization of 0.43 in (11 mm) lightweight unarmored fiber-optic cable (above).



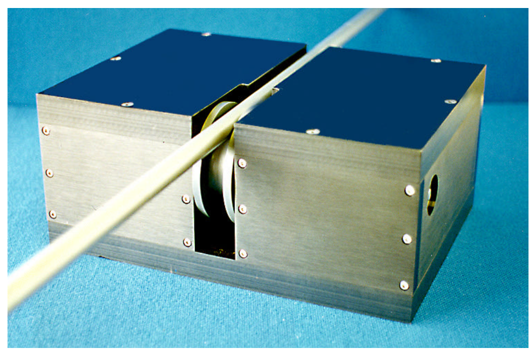
Artificial magnetization (above) permanently impressed on cable from figure on left.

In another test, a 2 in (51 mm) armored cable was magnetized and achieved signal strengths roughly the same as a 1.7 ft (0.5 m) diameter steel pipeline. Tracking this cable, it should be possible to calculate depth of burial at distances approaching 19.7 ft (6 m).



(Left) Side view of test magnetizer assembly positioned behind tractor assembly on the USN cable ship Zeus. The magnetic array disks are concealed beneath protective non-metallic covers. The disks (and covers) may be moved laterally to accommodate various cable diameters.

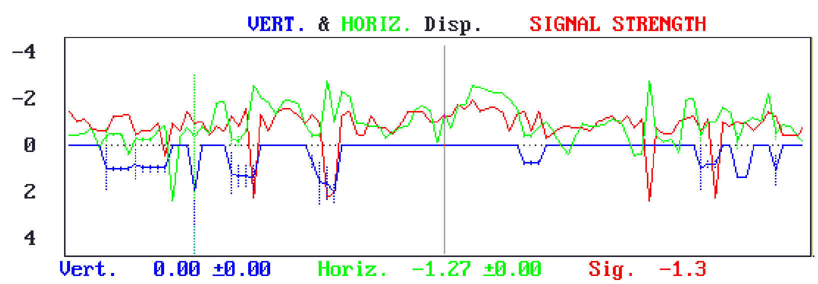
(Above) Actual size of 0.24 in (6 mm) subsea cable used in tests.



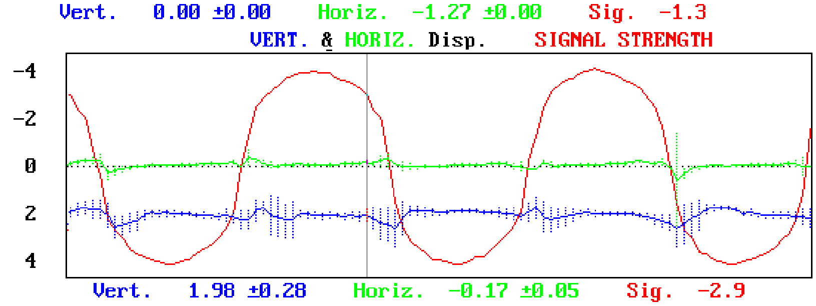
2-Axis cable magnetizer, suitable for smaller diameter cables.

Innovatum recently completed field testing their 2nd generation magnetizer (above right), which achieves higher signal strengths and cleaner field changes. A 0.24 in (6 mm) subsea cable was the smallest tested and the results, which follow, provided excellent correlation.

Before magnetization, 6.6 ft (2 m) survey of 0.24 in (6 mm) cable.

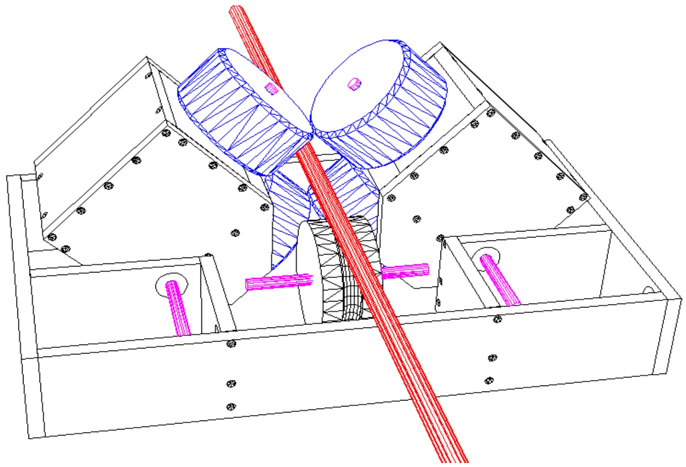


After magnetization, 6.6 in (2 m) survey of 0.24 in (6 mm) cable.



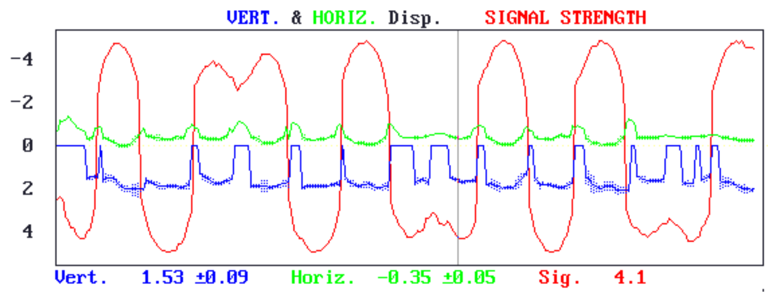
The plot in the previous "after magnetization" figure shows the dramatic improvement obtained as a result of magnetizing the cable. The horizontal and vertical position data are continuous and accurate. The slight ripple on both the horizontal and vertical tracking is due to slight deviations in magnetization along the cable, and could be reduced by using a 4-axis magnetizer as shown conceptually in the following figure, instead of the 2-axis model used for this test.

4-Axis cable magnetizer (right), suitable for larger diameter subsea cables, steel reinforced hydraulic hoses and small pipelines.



Innovatum's future plans include an ROV mounted model that could magnetize cable already laying on the seabed and a unit capable of magnetically encoding information on the cable that would be read by the tracking system to mark a location reference or cable identification. Proof of this concept is displayed in the following figure.

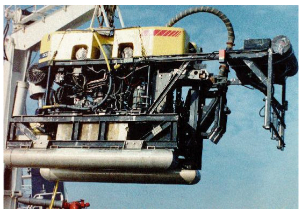
Survey record of a 0.43 in (1 mm) subsea cable that has data magnetically encoded.

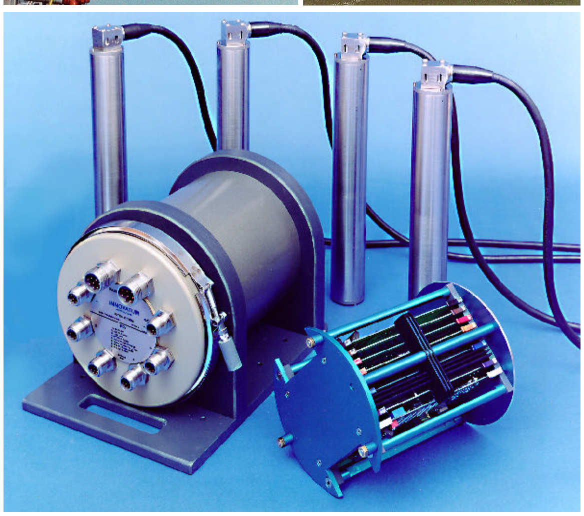


Using the Innovatum Ultra-System, tracking in Passive Magnetic mode, the burial depth of magnetized cable can now be monitored accurately without requiring an externally injected signal. With this technique, it is now possible to survey subsea cables without taking them offline.

The effects of artificial magnetization are permanent (natural de-magnetization is a very slow process with a time scale of centuries). The maximum field strengths impressed on cables by artificial magnetization are comparable to the natural magnetization of 1 to 2 ft (0.3 to 0.6 m) steel pipelines. These levels of magnetization have no effect on fish, sharks, whales or turtles.

The tracking algorithms of the Ultra-System are specifically optimized for passively locating artificially magnetized cables. The Ultra-System is also the only system that can offer simultaneous tracking of all known tracking modes: Passive Magnetization, Active AC (Tone), Active DC and Pulse Induction.





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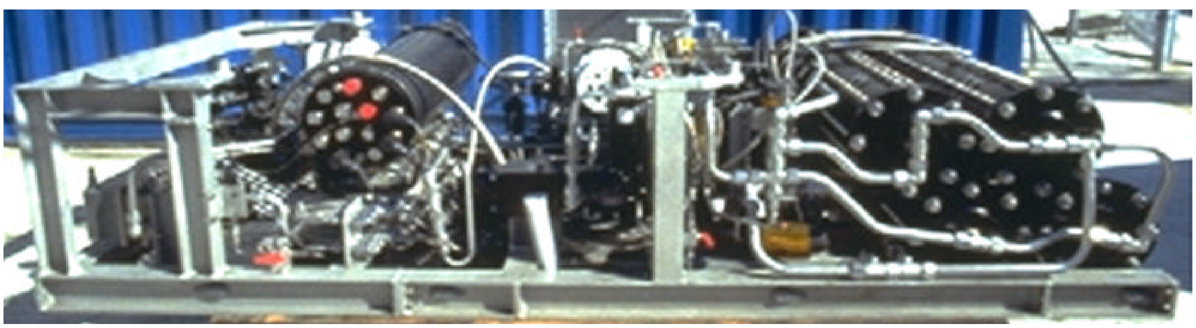
AUXILIARY WORK PACKAGES

General

Single task intervention requirements are normally met within the “spare” hydraulic and electric I/O (In/Out) capacity of work class ROVs. When operational procedures require completion of sequenced and/or varied intervention tasks, spare ROV I/O capacity can be rapidly absorbed. Spare I/O capacity in electric and hydraulic systems can also vary greatly from ROV to ROV, so reliance on this approach can cause integration problems, delay to projects and budget overruns. Auxiliary work packages are often the most efficient and sometimes the only method of providing complex and varied intervention services for field operators and installation contractors. The interface requirements for the skid can be specified to ensure the skid can be fitted to and integrated with any work class ROV of opportunity. This approach enables the operator or contractor to receive competitive ROV service bids from an acceptable number of ROV operating companies with the confidence that work skid integration can be successfully completed.



A typical auxiliary work package

Design Considerations

The following are general guidelines that should be applied when considering the design and integration of work packages. These guidelines are not placed in any order of importance.

- Work packages should lift level in air and exhibit level trim in water. The package should also be neutral or have a slight positive buoyancy.
- Total weight in air should be constrained by the through frame lift capacity of candidate ROVs.
- Total height of the package must take into consideration the clearance margin available between the candidate ROVs and their respective handling/over-boarding systems.

- The package must be able to handle the loads and forces experienced in deploying and recovering the ROV system. These forces and loads include the static weight of the ROV, and TMS, the forces applied by the handling system when landing the vehicle on deck and accidental impact with the vessel.

- ROV horsepower as quoted is often electric shaft-horsepower. Available hydraulic horsepower may be 25 to 30 percent lower than the published horsepower figures.

- Use of more than 50 percent of the actual hydraulic horsepower may adversely affect the ROV’s “flying” performance. If high utilization levels of hydraulic horsepower are required, consider docking or stabilizing the ROV.

- Use the ROV as a source of hydraulic power and primary AC electric power only. Do not rely on the availability of higher levels of DC power.

- Limited hydraulic control may be available. Control functions may be limited to piloting pressures and some pressure control. If complex control of pressure and flow is required, the work package may require its own hydraulic control components.

- Telemetry or computer connections to the surface may be provided by copper connection in the form of twisted shielded pairs or quads. The increasing use of fiber optic elements and fiber optic multiplex systems may also provide telemetry paths.

- Package frames are generally fabricated from aluminum, with either bolted or welded construction. Ensure all potential enclosures are drilled for flooding to avoid implosion at depth.

- The package must also contain the necessary systems and components to complete all the intervention tasks identified

Typical Applications

Intervention services provided by work packages include:

- Oil and water/glycol fluid transfer with pressure ranges from 500 psi to 10,000 psi and volumes from 0.5 US gallons to 50 US gallons

- Grease and sealant injection

- Seal removal and replacement

- Torque tool operation with typical torque values up to 2,000 ft-lb (277 kg-m).

- Linear override operation with linear pull to 10,000 lb (4,535 kg).
- Suction anchor pile installation
- Control pod and choke replacement operations
- Flexible flowline and control umbilical connection
- Pipeline cutting and recovery
- Platform cutting for removal operations
- Platform cleaning and inspection including ultra high pressure water cleaning and air or water entrained grit cleaning
- Ocean outfalls commissioning
- NDT services

Integration Issues

The ideal work package allows the field operator or installation contractor to select an ROV operator and have the package fitted to and integrated with an ROV of opportunity without the need for modification. The most likely scenario is that the intervention/engineering department of an ROV operating company will have built the package. It is further likely that the ROV operating company supplying the package will provide the ROV services for the first use of the package. The prudent operator will ensure the design specification contains the requirement for integration with a typical work class ROV of opportunity. Integration will normally consist of:

- Physical connection of the work package to the ROV. Connection can range from the simple insertion of load transfer pins to the requirement for engineered adaptation frames designed to handle the required stresses and loads.
- Hydraulic connection for supply of pressure and return of fluid.
- Electrical connection for AC and or DC power and telemetry

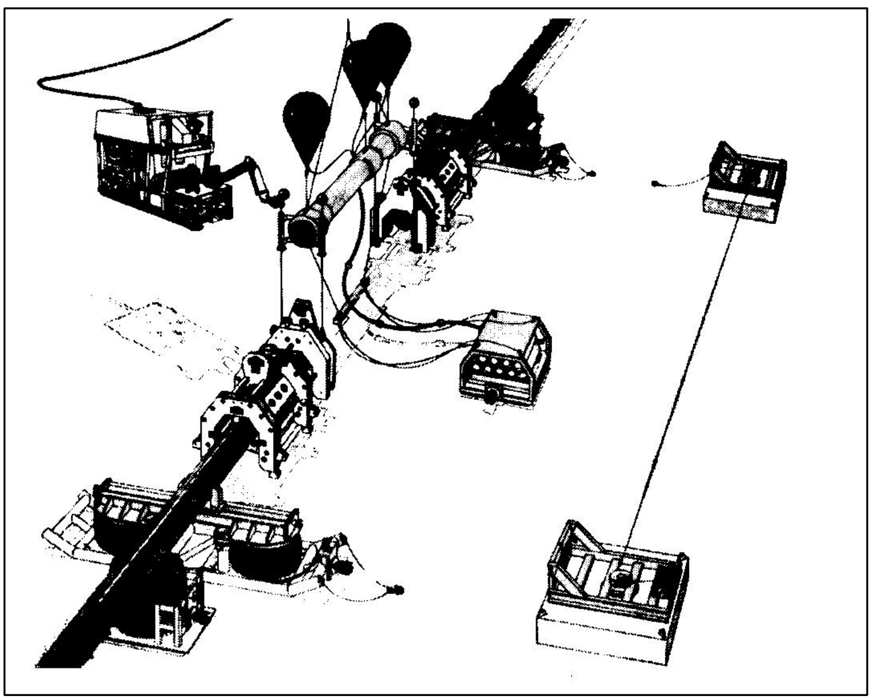
Auxiliary Work Package Example

An excellent example of an auxiliary work package is the Diverless Sealine Repair System (DSRS), developed by Sonsub, in conjunction with Saipem. The DSRS, which is intended primarily for deep water installations, incorporates the tooling aspects of remote pipeline repair with a specialized sealing system appropriate for remote diverless subsea pipeline connections.

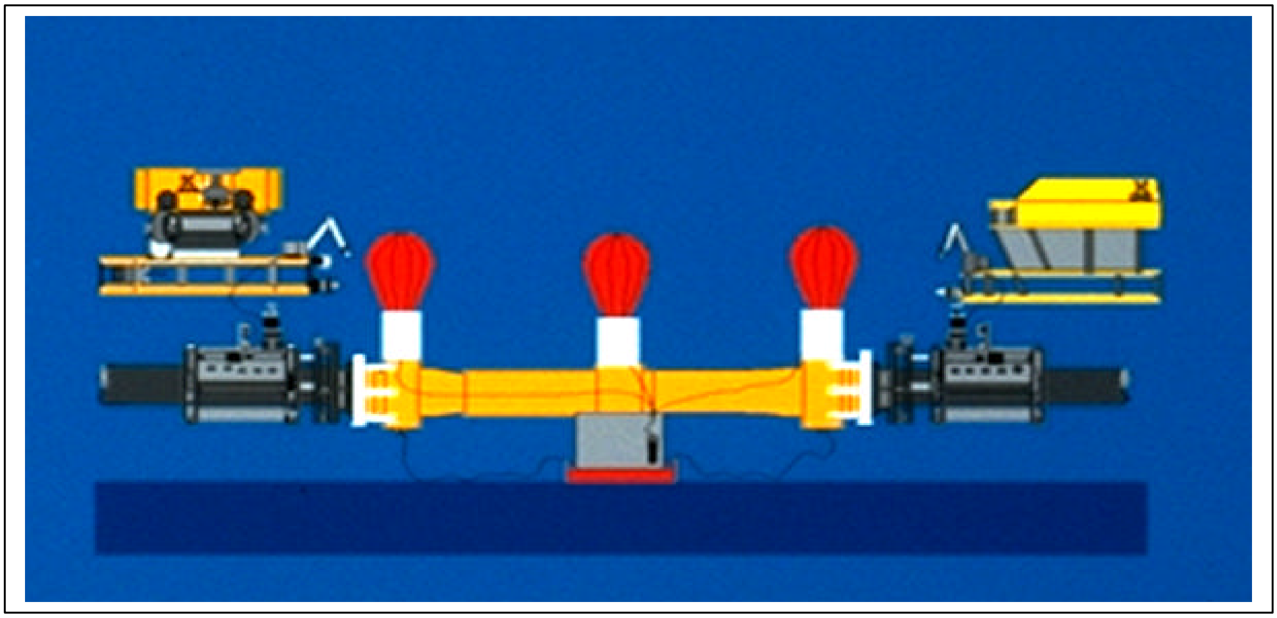
The DSRS is designed to be operated by an ROV without repeated trips back to the surface. Some of the key elements include:

- Two specially designed H-frames used to elevate the damaged pipeline from the seabed.
- Two water-inflatable pipeline support trestles inserted under the pipeline using ROV operated winches.
- Two Pipemate general-purpose universal pipeline tools, which can be interfaced to both the Tool Rotation Module and the Spool Docking Module.
- A pipeline replacement spool equipped with subsea buoyancy systems, to allow easy maneuvering of the spool by the ROV without dependence on surface lift.
- A Tool Rotation Module, which interfaces with the Pipemate and can be installed or removed subsea.
- The Pipe-end Preparation Tool (PPT) used to square the pipeline end and prepare it for the X-Loc seal, which was designed to allow installation, activation and seal testing by an ROV.
- A Pipeline Scissor Clamp used to remove debris.
- An ROV-deployed dredging system.

The following figures provide a perspective on the magnitude of the overall pipeline repair operation. The section of pipeline about to be inserted can be seen suspended by the underwater buoyancy system.



Key elements of Sonsub's DSRS (right)



Installation of X-Loc Spool

CHAPTER 7. OPERATIONAL CONSIDERATIONS

SUPPORT PLATFORMS

There is a large array of possible support platforms from which unmanned underwater vehicle operations can be conducted as shown in the figure below. These will be discussed in more detail in the following paragraphs.

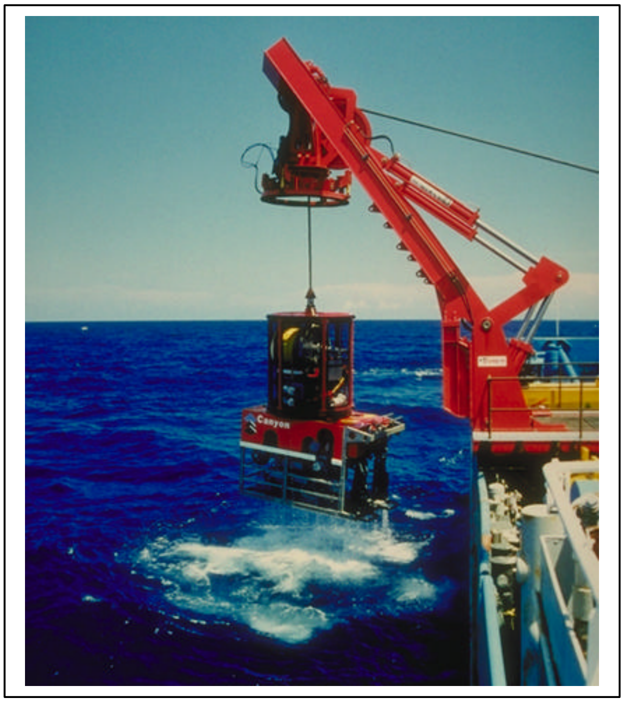
Ships-of-Opportunity vs. Permanent Installation

Two modes of operations should be considered before discussing the types of platforms available for unmanned underwater vehicle operations. These involve the use of a ship-of-opportunity, where a system is temporarily installed on the available vessel, or where it is installed on a dedicated support platform or ship. Cost and duration of the operation will be the determining factors in deciding which will be used.

In utilizing a ship of opportunity, overall costs may be considerably less. However, there will have to be trade-offs in the efficiency of the total system. Integration of navigation and control systems may be difficult, if not impossible. Mobilization and demobilization costs (both in dollars and time) will have to be taken into consideration when using a ship of opportunity. In the case of a permanent installation on a support platform, some integration can be incorporated during the installation phase.

The lack of purpose-designed handling gear, especially for larger vehicles, places rather severe restrictions on the selection of a suitable support platform. The use of some arbitrary crane or derrick often leads to dangerous situations and will, in most instances, increase the weather dependence.

A purpose-dedicated support ship, which is designed for the primary function of supporting ROV operations, has advantages over a ship-of-opportunity or permanent installation on multi-function vessels. The reason being that all considerations peculiar to ROVs can be accommodated in the initial design and construction phases.



Platform Types

Regulations exist, setting down clear standards, that must be met by all equipment operated from fixed and floating platforms. These may inhibit the operation of some ROVs if they do not meet these standards, including, in some cases, a requirement for electrical systems to be explosion-proof.

The basic problem when conducting operations from fixed or floating platforms is the fundamental requirement to be able to sight the ROV and its support equipment on all sides in order to minimize problems of entanglement of the ROV or its tether. With space being at a premium on these structures, this is often not possible. Consequently, such work is frequently carried out from a ship or barge alongside the workstation.

In the original Guidelines, platform installation was described by the following, which is worth repeating: “The location allowed for the ROV system will most often not be designed for the system. It will probably have been selected as an afterthought, will be crowded, noisy and dirty. The overhead will either be too low or too high. The system, when installed, will be subjected to rain and saltwater, drill mud and chemical splash. The location will probably be shaded from the sun in cold climates and exposed to the sun in hot climates. It will be physically shaped like a wind tunnel and the operators will always be cold. It will rarely have a solid deck, so any item or tool dropped will probably be lost overboard. Otherwise, most locations are perfect.” Although many of those comments may still be appropriate, platform integration has advanced to the point where the incorporation of ROV systems are no longer an afterthought, and–for those who do it properly–they are integrated early in the design so that support requirements are fully met. The various types of platforms will be discussed in the following sections.

Monohull

The term "monohull" refers to a craft or vessel whose structure consists of a single hull. This is in comparison to, and to differentiate from a "multihull" (catamaran or trimaran). The monohull support platform is more versatile than other types of hulls in that it can withstand more severe sea conditions, is generally more maneuverable and can handle considerably greater payloads. Monohulls can be highly maneuverable, especially if equipped with bow only or bow and stern thrusters. Also, the construction costs of a monohull are considerably less than for multihulls. The overall advantages of monohulls are demonstrated by the comparative numbers of these types of vessels as compared to all other types.

Japan's new *KAIREI* deep sea research vessel

One of the newest and most sophisticated monohull platforms is Japan's new *KAIREI* deep sea research vessel. *KAIREI*, meaning "oceanic ridge" in Japanese, is designed to engage in surveying deep sea bottoms, such as trenches, by serving as the exclusive mother ship for the 32,808 ft (10,000 m) ROV *Kaiko* (which means "trench"). The 344-foot (105-m) vessel is equipped with the latest equipment to allow ROV operations in any ocean depth. The *KAIREI* (shown below) is operated by the Japan marine Science and Technology Center (JAMSTEC).

Catamaran

The term "catamaran" refers to a craft or vessel whose construction consists of two hulls fastened together. The main support platform is built on top of the structure that fastens the two hulls together. The advantages of the catamaran type of work platform are that in average sea states, around six feet or less, they tend to be more stable and sea-kindly. They tend to have larger deck spaces but are very limited to the amount of payload that can be carried aboard. Below deck working and living spaces are very limited in that the individual hulls are considerably less than 1/2 the breadth of the vessel. Catamarans are generally not as maneuverable as monohulls and to achieve any degree of maneuverability require the use of multiple thrusters installed in each hull, either in the bow or in the bow and stern configuration.

Semi-submersible

The term "semi-submersible" refers to a vessel or craft that has the capabilities of taking on or off-loading ballast water to rise higher in the water for transit and to settle lower when at the work site. With the vessel in a dewatered condition draft is, of course, reduced allowing it to navigate in shallow waters. The reduced draft also reduces drag and therefore saves on fuel costs. In the ballasted condition, draft is greatly increased and the wetted surface is greatly reduced. With the wetted surfaces reduced, the actions of waves have very little effect on the vessel. These vessels provide a very stable work platform, particularly for conducting over-the-side operations commonly associated with ROVs. Semi-submersibles are generally catamarans but the definition does not limit the construction to two hulls. Many offshore drilling platforms have semi-submersible capabilities in that they can be ballasted and dewatered to provide a combination of stability and mobility.

The disadvantage of semi-submersible vessels is primarily one of cost, and complexity of the ballasting system. As with catamarans, payload is also very critical and restricted as well as below deck living and working spaces. Gross maneuvering is very difficult with semi-submersibles, and multiple thrusters are imperative for positioning and station keeping. This type of platform is particularly suited for dynamic positioning systems.

An example of a state-of-the-art semi-submersible is Global Industries Ltd.'s newly completed multi-purpose support vessel (MSV) *Pioneer*. The small waterplane area, twin hull (SWATH) vessel is 200 ft (61 m) long, has a beam of 87 ft (26.5 m) with 9,000 square feet (836 square meters) of deck space. Its two moonpools support a saturation diving system and a fully dedicated *Triton XL*+ ROV. The vessel's bow and stern thrusters provide dynamic positioning while aided by a dual redundant Nautronix ASK 4002, with a Nautronix TCS thruster control system. Combined with GPS data, the vessel (shown on the following page) is an excellent platform from which to conduct ROV operations.

Global Industries Ltd.'s *Pioneer*

Fixed Platform

Fixed platforms have the obvious advantage of being physically fixed to the ocean floor and therefore are the most stable of offshore platforms. Their function as a work platform for ROV or manned submersible operations is secondary to their prime function as an offshore drilling or production platform. Payloads and stability are generally not of concern to this type of platform. The disadvantage of this type of platform is immobility. Once the platform is in position and operational, it is very difficult if not impossible to move without major reconstruction.

Inland "Platforms"

Operation from inland "platforms" such as dams, bridges, or other stationary structures have a different set of problems. The depth of operations can be considerable, or hazardous, to the extent that an ROV is warranted versus a diver. However, the biggest problem is usually access for the ROV system. Small dams or other locations may not have roadway access to include access across the top, or may not have usable top structures. Power will generally be far away in many cases, requiring the use of portable systems. The water level may be far below the top of the dam or structure, thereby necessitating a floating platform, or a method of lowering the vehicle to the water. Unlike offshore operations where large platforms can maneuver over the work site, inland operations can pose a very unique set of problems. See the Inland Operations section in Chapter 2.

Ice

Ice floes have been used in the Arctic as work platforms for ROV operations where conditions prohibit the operation of surface craft. The time window is very critical and year-round operations are impossible. This type of platform has been used historically for research, archaeological or documentary purposes, but more recently–as demonstrated with the Theseus vehicle–has been used as a base to install underwater surveillance arrays.

Some of the considerations regarding the use of ice as an ROV support platform follow:

- The thickness or strength of the ice may not be adequate to support the weight of the ROV system, or the system may have to be spread over a large area to distribute the weight adequately

- Cutting holes in the ice can be difficult. Cutting a hole of sufficient size for a large ROV can be nearly impossible without proper equipment

- Preventing the opening from freezing over must be considered, along with temperature variations that the ROV may encounter during routine maintenance and launch

- Ice floes fracture and form leads that may hamper operations and can be disastrous, especially when connected to equipment below while the floe moves onward

- Land fast ice is most often an extremely stationary platform from which to work

Submersible

Man-rated submersibles have been used as work platforms for ROVs. Recent investigations of sunken platforms such as the *Titanic*, along with the ever present documentaries, have proven the utility of such symbiotic relationships. This mode of operation extends the capabilities of the manned submersible allowing access to areas that are too small for the submersible, and also eliminates the long umbilical back to the surface, which would increase the difficulty of such interior or close-up inspections.

A mounting or retaining structure must be provided for the ROV to adequately protect and retain it during launch and recovery, and when subjected to the current forces it may experience at the "mother" submersible's normal and maximum cruising speeds, either surfaced or submerged.

Other

Today, with the LCROV becoming very popular, the available platforms they might be operated from can cover a broad range, as shown in the following figure. Although an inflatable boat is not the most optimum operational platform, it shows that, based on the size of the vehicle, there are many options available to the dedicated operator.

DOE's *Phantom* being launched

Live Boating

Live boating is the term used for the deployment and operation of an ROV from a non-stationary vessel. Maneuvering and station-keeping capabilities of the intended support vessel must be carefully considered. Does the vessel have single or twin screws and are the screws caged? Does the vessel have a bow thruster to assist in maneuvering? Many ships-of-opportunity have twin screws, but no bow thruster.

The job tasks must be defined (i.e., must the vessel hold station for long periods of time or will it be following the ROV along a pipeline?). The ROV umbilical or tether should be positioned over the ship's side away from the screws and bow or stern thrusters. The method of tracking the ROV must be considered since the only reference to the vehicle may be the direction in which the umbilical leads away from the ship. In this case, the umbilical should be tended over the side at a point where the vessel's operator can observe the angle. If an acoustic tracking system is to be used, the display should be available to the vessel operator.

Ideally, the vessel should be equipped with a dynamic positioning (DP) and control system. This DP system could be used in conjunction with the acoustic tracking system to enable the vessel to automatically hold position relative to the ROV or follow the ROV along the pipeline (if that is the task).

The qualifications and experience of the ship's Master and his relief operators are a major consideration. The vessel operators must be thoroughly briefed and familiar with live boating and the capabilities of the ROV operators and their system.

Sea state and weather limitations of the vessel will be determined by its ability to maintain station relative to the ROV. Most ships-of-opportunity are unable to maintain station against a combination of strong currents and high winds. Generally, most live boating operations will have to be terminated at about sea state five to six, depending upon the vessel in use.

Communications between the ship's bridge (vessel operator), the ROV control van (ROV operator) and the deck crew adjusting the ROV umbilical is critical. Any misunderstanding or failure in communications could result in the loss of the ROV, its cage or both. Hardwire voice communication is the most dependable technique. It may be backed up by.radio, public address or visual contact.

In the case of a purpose dedicated ROV support ship, considerations regarding station-keeping characteristics would include the following:

- The concept of dynamic positioning should be central to the design philosophy of an ROV support ship. This permits complex and protracted vehicle operations around active subsurface facilities without the dangers related to deploying anchors or the inherent operational risks of manual "live-boating"

- Stability in an ROV support vessel facilitates safe deployment and recovery of the ROV and safety and accuracy of subsurface operations involving operator comfort. The result is accurate operator orientation at the worksite and more efficient performance of mid water and manipulative tasks. A stable vessel is also essential for rapid and efficient maintenance of the ROV during operations in marginal sea conditions

- The auto-heading capability of some dynamic positioning systems can also be used to hold the vessel's bow into the prevailing weather, further improving over-all vessel stability

GENERAL PROCEDURES FOR THE OPERATION OF ROV SYSTEMS

Introduction

The purpose of this document is to provide ROV personnel with a general description of the procedures to be followed offshore, and is adapted from procedures provided by Oceaneering International Inc.–"the Company." Specific Procedures for each type of vehicle operated are contained in the ROV Department Procedures referenced below.

This document Highlights a number of Technical and Operational considerations and reinforces the role of individual project managers and superintendents to ensure that ROV Operations are conducted safely, professionally and efficiently

While the operational procedures vary from system to system, due to their primary design and work tasks, the basic subdivisions to which this document relates are "Tethered" and "Free Swimming".

Definitions

- Tether Management System - An ROV lifted within a cage or underneath a tether cable management, winch/depressor system.
- Free Swimming - ROV operated via its "armoured" or "soft" control cable.
- Dynamic Positioning (DP) - Computer based vessel propulsion control system.
- Header - Titling by video annotation and audio commentary at start of video recording.
- Black Box - Unedited video recording of operations without pause and interruptions to ensure total coverage of events.
- Beaufort Scale - Oceanographic measurement of sea state conditions.
- ADC - Association of Diving Contractors.
- OSHA - Occupational Safety and Health Administration

Operational Procedures

It is the responsibility of the Senior Offshore Representative to ensure the designated work tasks are accomplished in a safe and efficient manner and in compliance with contractual obligations.

Presented in detail in the System Operating Procedures, the procedures maintain minimum standards and work task schedules for any ROV Operation. Where required, any, or all, will be supplemented by detailed "worksite specific" procedures.

Operating procedures have been developed for two principal ROV types - "Tether Management Systems" or "Free Swimming".

Where necessary, differentiation between "tethered" and "free swimming" operations will be highlighted.

Dive Preparation, Launch and Recovery

The ROV Supervisor and his team shall carry out the following principal tasks prior to commencing the workscope:

- Carry out a comprehensive crew briefing.
- Notify third parties associated with the operation.
- Prepare the ROV for the work task and complete pre-dive procedures and checklist.
- Deploy the ROV and locate the worksite.
- Upon completion of the work task, recover the ROV.
- Complete Post-Dive procedures and checklist.

Operation from Vessel using Dynamic Positioning Systems

The following principal points shall be noted in all ROV operations from vessels utilizing a DP system:

- The ROV shall not be launched or operated near a taut wire reference system.
- The ROV control van would ideally be equipped with an alarm warning of impending failure or loss of DP and when 70 percent of available DP power has been applied.
- Vessel shall not be moved or taken out of DP mode without the prior knowledge of the shift ROV Supervisor.
- The ROV shall be launched as far away from thrusters as practical, taking special note of azimuthing units.

- Umbilical winches shall be manned at all times.
- Vehicle buoyancy shall be slightly positive.
- Good communications must be established between the ROV control van and the bridge to ensure that the ROV Supervisor is in constant contact with the bridge and is aware of all actions regarding the relative positions of the ROV and vessel.

Operation from Semi-Submersibles and Fixed Installations

In general, offshore installations and semi-submersibles operate Permit-to-Work Systems. These systems must be adhered to and fully understood.

The Control Room must be informed prior to commencing the dive and all relevant Permit-to-Work raised.

When operating in a hazardous area, the detection and shutdown equipment must be checked at regular intervals.

When launching and recovering the ROV, attention must be paid to any submerged members of the installation.

"Tethered" vehicles are preferred to "Free Swimming" ROV systems due to their superior umbilical management systems.

The ROV must not be operated within the "Splash Zone", without specific authority from the ROV Operations Manager.

Where ROV operation is required within the structure, great care must be taken to ensure that the tether or umbilical is not snagged or damaged.

Operations with Divers

"Tethered" vehicles are preferred to "free swimming" ROV systems because of superior umbilical management systems.

Prior to and during operations that carry an increased risk to the diver the following shall be strictly adhered to:

- No ROV shall approach closer than 3 m from the diver until instructed by the Diving Supervisor.

- The ROV ground fault detection shall be fitted and operational.

- All thrusters shall be fitted with guards.

- The ROV shall never cross the diver's umbilical or swim around the bell umbilical.

- Emergency signals and recovery procedures for diver, bell and ROV shall be agreed to and understood prior to the start of diving operations.

- The diver shall always leave the worksite first. The ROV can then clear the site, after having received confirmation from the Diving Supervisor. After discussing the work task with the Client's Representative, and obtaining all available information and the required reporting forms, the ROV Supervisor shall brief the crew.

Video Recording and Reporting

The majority of ROV related work scopes rely on the ROV's quality of vision using a choice of video sensors and a stable platform to accomplish inspection and observation tasks of varying complexity. The management of these recordings is of critical importance in any project workscope.

The following key points shall be adhered to unless modified to a specific workscope:

- Only blank "new" tapes are to be used; never use an entertainment tape.

- Tapes are to be referenced with a Client agreed standard "header" and audio voice-over of same information.

- Video recordings shall be carried out on a continuous basis. Any pauses shall be noted on the audio track.

- On completion of recording, the label shall be annotated with the relevant dive/worktask details and stored with a copy of the video log in its storage box.

- For "observation" work scopes or similar, ROV data should be stored on the video tape in a "black box" mode, re-using it after each dive.

Environmental Limitations

Maximum weather operating limits are set by the operating company's insurance warranties and are not to be exceeded under any circumstances other than that provided for in the Indemnity Form.

Within this section, sea state and wind force tables that are presented shall be used as guidelines to any decision required on weather conditions and operating limits. It is noted that vehicle placement, support vessel characteristics, ancillary/project equipment, etc, may cause these upper limits to be revised downwards and that the safety of personnel takes precedence over equipment utilized.

The following environmental limitations are the maximum conditions under which vehicles can be operated within the terms of the Company's Insurance policy (in this case the company is Oceaneering). Note that combinations of conditions, task, and support vessel/platform can cause lower values to be unsafe. The ROV Superintendent/Supervisor has the final decision as to whether the weather and/or operational conditions are operationally safe. **The vehicle shall not be operated in unsafe conditions.**

Water Depth

- Minimum - No work shall be conducted in water depths of less than 20 msw without prior approval from the onshore ROV Operations Manager.

- Maximum - This shall not exceed the design rating of the ROV, unless specifically modified for a defined purpose. The ROV Technical Manager is to be notified of any technical changes affecting Operational Depth Limits.

Sea State - 5 to 6 "Beaufort Scale"

Wave Height - 4 m (13.1 ft) average wave height

Wind Speed - 14.4 m/sec (28 kt)

Current

- Head on = 1.29 m/sec (2.5 kt)

- Side on = 0.77 m/sec (1.5 kt)

Note: These values are variable and dependent on the length of tether deployed and the direction of the current.

Underwater Visibility

- Around structures and/or debris - 2.0 m minimum
- Open water - 1.0 m minimum
- Practical video inspection - 2.0 m minimum

Tunnels, caves, etc

The vehicle shall not enter such confined locations unless clearance has been received from the Onshore Operations Manager.

Insurance Warranties

The following guidelines review the fundamental principles associated with the subject and the minimum responsibility of the Company.

Note that insurance is not a licence to operate dangerously. If the warranties and guidelines are not properly adhered to the insurance will be invalid.

Limitations

The declared equipment shall only be operated by approved staff, or personnel under contract for the project workscope.

Piloting of the ROV by an individual must not exceed 8 hours within a 12-hour shift. Thereafter the individual must take a minimum break of 8 hours within a 16-hour period.

Underwater vehicles shall not be launched or recovered when weather conditions exceed Company and Insurer limits.

The declared equipment shall not be operated in conditions that exceed the manufacturer's specified operating parameters except where the equipment has been purposely engineered for a specific task.

Special precautions shall be taken when operating from dynamically positioned vessels to ensure that vehicles are kept clear of thrusters and tautwires.

Underwater vehicles shall not be operated in poor water visibility (less than 2 m) unless sonar is in use, however, this warranty shall only apply when undertaking operations outside a confined area.

Prior approval of the Insurance Company is required when operating declared equipment in unusual or hazardous circumstances, for example:

- Blowouts
- When using explosives except where contracted to explosive specialists/experts or fully qualified Principals in this field
- Operations not normally undertaken within confined wreckage or structures, i.e. outside of the normal practice of Inspection, Maintenance and Cleaning
- Operations within wave surge zones or in the proximity of heaving moorings and/or objects where heave is greater than 1-2 m.

Suitable precautions and preservation/maintenance measures shall be adopted when storing, handling, transporting and operating declared equipment.

Direct communication shall be maintained between the vehicle pilot and the control station of the vessel. The vessel crew shall be properly briefed on ROV operations.

Indemnification Agreement

This agreement confirms that the Client shall indemnify, hold harmless and defend the Company for loss, damage and liability in respect of operating unmanned ROV systems in conditions of bad weather, dangerous situations or environmental hazards, such as blowouts, which are outside the terms of the Contract and/or expose the equipment to loss or damage by extending the operation of the equipment beyond the operating limits.

Vehicle System Failure

This section outlines the general procedures to be followed in the event of vehicle failure. Vehicle specific procedures are available within the specific Operating Procedures documents, which give detailed instructions on the subject.

Failures can be categorized into two principal areas - hardware and software.

For each vehicle type, specific procedures have been developed to assist ROV personnel to efficiently deal with each operational incident. These range from vehicle failure to umbilical separation.

These vehicle specific procedures are presented in the Operating Procedure for each system (see next section on Specific ROV Operating Procedures).

Maintenance

Equipment maintenance forms a vital part of a safe and operationally efficient ROV operation. Planned maintenance systems can achieve substantially reduced downtime.

System schedules ranging from simple pre-dive checklists through to detailed planned maintenance procedures must therefore be used to attain and maintain the highest possible standard of operating efficiency.

All work shall be undertaken in compliance with supplier's/manufacturer's recommendations.

Each ROV system type is provided with a full set of vehicle manuals and vendor subsystem technical information to enable efficient maintenance and re-ordering of system spare parts.

ROV system maintenance is divided into the following main areas of documentation:

- Operations and maintenance manuals and drawings
- Suppliers manuals and drawings
- Catalogs of equipment

The above includes the following key subsections:

- Vehicle maintenance procedures

- Subsystem maintenance procedures, i.e. video cameras, sonar system, pumps/motors.

Detailed repair and maintenance procedures are to be found in the specific ROV Operations Manual.

All equipment shall be suitably labelled to indicate its operational status, on arrival at the ROV Operational Base, in accordance with Company Procedures.

Safety

The Company (Oceaneering) places great emphasis on safe practice at all levels of business, both on and offshore.

To fully support this policy and philosophy, a Company-wide safety plan has been in place and improved upon over the years. Supplied to each department and offshore system, the Safety Manual enables the user to build on the in-place structure and produce a worksite safety plan at any location.

Policy

Safety is paramount and shall not be compromised.

Responsibilities

Each person shall be responsible for the safety of himself and his co-workers. The Managing Director has overall and final responsibility for Health and Safety in the Company.

Offshore, the ROV Supervisor is responsible for himself and the team to ensure that safe working practices are set up onboard at the start and maintained throughout the project duration. These responsibilities are primarily the application of safety standards and procedures laid down by Company, Health and Safety Executive, MMS, ADC, and OSHA Regulations.

Reference to all these documents shall be made when a worksite safety plan is laid-down at project start-up.

On-site safety meetings shall be held and recorded in writing, where no mandatory requirement exists on the Vessel or Installation. Copies of meeting notes shall be sent ashore for the attention of the ROV Operations Manager and Regional Safety Officer.

Accidents

All accidents, however small, shall be logged in the on-site accident book with a written report in the standard format as soon as possible to the Regional Safety Officer and the ROV Operations Manager. Accidents shall also be logged with the Client's offshore safety person in compliance with their accident reporting format.

Fire Safety

Company staff shall maintain and enforce the worksite installation fire safety standards and comply with the requirements for regular fire drills, etc.

ADC Electrical Regulations

ADC rules for "Use of Electricity Underwater" shall be complied with at all times. System electrical equipment shall be maintained to ensure these technical standards are fully met.

Machinery

All machinery shall be operated in a safe manner. Particular attention shall be paid to use of guards while operating. Refer to specific equipment operation and maintenance procedures at all times.

OSHA

All staff shall comply with the Company's strict adherence to the current OSHA Regulations.

Reference shall be made to the manufacturers data sheets and handling procedures to maintain safe utilization of all materials.

Personnel protection, i.e. clothing, eye/head/hand and footwear, shall not be neglected when handling any hazardous substances.

Emergency and Mayday Procedures

An established written Company based "Emergency and Mayday Procedures" applies to all Company offshore work sites.

Copies of this document are located in each ROV worksite control van providing detailed instructions in the event of an ROV or ADS incident along with emergency contact numbers of Company Operations and Safety Officers.

Administration

Operational Structure - ROV Department

ROV Department operations, managed from the Operations Office, provides the day-to-day management of ROV systems operating in the region and directly interfaces with the Clients for all ROV, ADS, and associated underwater services.

On award of contract, each ROV system shall be identified or re-confirmed. At the same time, a dedicated onshore ROV Project Manager shall be appointed, together with onshore System Supervisors and mobilization team.

Any project-specific inter-department links shall be put into place at this time.

Notice of these links shall be formally communicated to the Client along with all required exchange of paperwork systems including contract references, etc.

Onshore briefings shall take place between:

- Client and ROV Operations Department assisted as required by the Company's other internal services, i.e. Commercial, Logistics, Legal, etc.

- ROV Operations and offshore ROV Supervisors.

Documentation

A structured procedural approach to all levels of business management including documentation will be maintained. (See section on Documentation of ROV Operations)

These include information required for the start up and ongoing, efficient and safe running of operations, and the provision of documentation required as backup to the Client.

The following are completed offshore by the ROV team on a "daily" and "as required" basis:

Daily:

- ROV Job Status Report
- Daily Time Ticket

As required:

- Fax Report
- Maintenance Logs
- Downtime Report
- Equipment Failure Report
- Pre/Post Dive Checklist
- ROV Payroll Form
- Video/Photo Log Sheet
- Equipment Movement Order (EMO)
- Purchase Requisition
- Transportation Request

SPECIFIC ROV OPERATING PROCEDURES

Introduction

The following procedures were developed by Oceaneering for use with their *Challenger* ROV systems. They have been adapted for this publication to provide more insight into specific areas that must be taken into consideration by the ROV operator. Sample maintenance logs are also provided for several of the ROV systems.

Crew Briefing

After discussing the work task with the Client's Representative, and obtaining all available information and the required reporting forms, the ROV Supervisor shall brief the crew. To be discussed are:

- The work to be accomplished
- The route the ROV is to take to the work site
- The data to be collected and how it is to be recorded
- Ways of accomplishing the task are to be discussed and a procedure agreed
- Crew positions will be assigned
- Emergency procedures

Notification of Operations

The Supervisor must ensure that all other personnel/parties affected by or having an effect on the ROV operation are notified of the intended operation, to include:

- The Offshore Installation Manager (OIM) on offshore platforms (check the individual platform as well as the Manager for the Field)
- The Vessel Master
- The Diving Supervisor
- The Deck Foreman/Shift Superintendent

The Supervisor is to ensure that he knows of any planned vessel, diving or technical operations that may interfere with or curtail the planned operation. He shall also obtain the latest weather forecast.

Vehicle Preparation

Vehicle preparation consists of preparing any tool or work packages, ensuring that they interface correctly with the vehicle and its controls, and then conducting the pre-dive checks of the entire system. On completion of the checks, it shall be logged on the Dive Log sheet.

The Supervisor shall assign the crew members the various preparatory tasks and ensure that they are completed satisfactorily using the checklist supplied for each sub-system.

When the pre-dive checks have been completed the vehicle is ready to be launched. If any items are shut down in the period between completion of the pre-dive checks and actual launch, e.g., due to a long delay for other vessels operations or weather, the relevant checklist(s) shall be used again.

Work Task

For efficient performance, the following task related information shall be available to the Supervisor/Superintendent prior to the start of work on the task. This shall allow pre-planning and pre-dive briefing of the crew.

- Written job request detailing the specific requirements of the task

  - What is to be done
  - What results are expected
  - What information is to be gathered and how it is to be recorded

- Relevant drawings of the structure/vessel.

- Location co-ordinates of the subject.

- Up-to-date chart of the underwater topography showing pipelines, structures, hazards, etc.

- Any relevant historical information, especially of any previous ROV or diver work and construction or as installed/built photographs.

- Period available for the task to be completed.

The Supervisor and the Client's Representative shall select the task from the Scope of Work. An additional/alternative task may be selected in case the primary task is superseded by other priorities.

The Supervisor shall make all possible efforts to find a task that is not affected by Client's other priorities.

ROV Deployment

When the notification procedures have been completed the crew shall take up their nominated stations:

- Vehicle control station - Pilot
- Winch/"A" frame - Pilot
- Deck handling - Supervisor

Prior to deploying the ROV overboard, the Pre-Dive Checks shall be completed and a final check of tooling status, system lighting, removal of camera caps and ground strap shall be completed. The following steps shall be followed during deployment, operation and recovery of the ROV system.

Use of "A" frame

- The ROV/TMS unit shall be lifted from the deck by the umbilical and latched into the "A" frame head pulley. Winch Operator and Supervisor shall confirm visual indication of latching.

- The ROV/TMS unit shall be rotated by the turntable, if necessary, to allow the unit to pass between the legs of the "A" frame.

- The ROV/TMS shall be swung over the side and unlatched from the pulley.

- The unit shall be lowered to the proximity of the splash zone.

- The rate of descent shall be reduced during the transition period as it can be advantageous in certain sea conditions to slow the entry of the ROV/TMS into the water.

- Once the ROV/TMS is in the water the Pilot shall power up the ROV and TMS hydraulics and conduct a status check on all alarm systems.

- The Supervisor shall move to the control container.

- The Winch Operator shall be kept informed of the vehicle depth by the Pilot during the descent to the planned release depth.

- When the ROV/TMS reaches the planned release depth the winch shall be secured and switched off.

- The ROV control crew shall conduct the subsea checks prior to the vehicle leaving the TMS.

TMS - ROV Separation

- Pilot and Supervisor shall both be satisfied that the in-water checks have been completed correctly and that the results are within acceptable ranges.

- Conduct a final check of the following underwater conditions:

  - visibility
  - current speed and direction
  - swell effect if operating near the surface

- On completion of all checks the latches shall be released and the ROV shall be manoeuvred away from the TMS.

- Before proceeding to the work site the ROV shall conduct a survey of the TMS.

- While travelling to the work site the Pilot shall monitor TMS functions and watch out for objects that may possibly entangle the tether on recovery.

Locating the Work Site

- The pilot shall use vehicle data (depth, heading and sonar) in conjunction with the vehicle's SIT camera(s) to drive to the work site with a minimum of delay.

- The Pilot shall keep to the pre-planned route, current, visibility, and debris allowing.

- The route shall contain an absolute minimum of travel within any structure.

- A feature, which can be positively identified, shall be used as a navigational fix. A series of these shall be used where long distances must be traversed.

- During the transit to the work site, the tether shall be managed by using a combination of the aft SIT camera (if fitted), the pan and tilt camera, the TMS camera (if fitted), and the tether counter. Ensure that excessive amounts of tether are not spooled out and that entanglement on a structure or with debris is avoided.

ROV Recovery to the TMS

- Switch on the TMS light.

- As the Pilot navigates the vehicle back to the TMS, using the aft SIT camera and the pan and tilt camera, the tether shall be wound back by the TMS winch.

- The winding in of the tether shall be closely monitored by the Pilot using the tether counter, TMS camera and the vehicle's aft and pan and tilt cameras to ensure that it is not being damaged by any projections or possible sources of entanglement.

NOTE: The Pilot shall have logged possible entanglement or damage causing areas while travelling to the work site.

- The TMS light shall be switched off when the TMS becomes visible.

- When most of the tether is re-wound, the vehicle shall be positioned below the TMS and slight down thrust selected in order to tighten the tether before docking.

- The tether shall be spooled in until the docking cone is positioned correctly within the TMS. There is no critical direction or attitude required of the vehicle during this procedure.

- When the docking cone is positioned correctly, the main and fail-safe latches shall be activated.

Recovery of the ROV/TMS to the surface

- When the vehicle indicates a "Latched" status within the TMS, the post-dive in-cage checklist shall be completed.

- The ROV/TMS assembly shall be winched to the surface. The Pilot shall remain in the pilot's seat until the vehicle is on deck. Just below the surface, the ROV and TMS hydraulic circuits will be switched off.

NOTE: It is normal not to slow down while transiting the splash zone.

- When the TMS is latched into the pulley, the deployment procedures shall be reversed, the assembly brought on deck and the ground strap fitted.

- Vehicle power shall be disabled on completion of the post-dive checks and it shall be logged on the Dive Log sheet.

Emergency Recovery Procedures

- Outline recovery procedures are provided within each system in the event of ROV entanglement, disablement or loss.

- Worksite specific procedures shall be produced for each contract workscope. These shall be based on the ROV systems in-built capability of self-rescue, the worksite conditions, environmental factors and operating platform facilities.

- The availability of local third party facilities, i.e. divers, is also a key factor in any contingency planning as is the area knowledge and assistance of the Client.

Actions in the Event Of Failure

In the event of any failure in the ROV System the ROV Operations Base shall be informed.

Hydraulic Failure

Single HPU Failure

- If the fault is electrical the HPU will be shut down automatically.

- If the fault is mechanical the HPU shall be shut down manually.

- The vehicle shall be recovered in the normal fashion using the remaining HPU(s).

Total Hydraulic Loss

- Switch off all HPUs.

- If the vehicle/tether arrangement is such that the vehicle could rise to a level where it could be a hazard to shipping, immediately notify:

  - The Master of the Vessel if operating from a vessel, or
  - The OIM or Platform Supervisor if working from a fixed structure

- Request that they notify vessels operating in the vicinity to stay well clear until the vehicle is recovered.

- Determine the vehicle status and location using its cameras and sonar.

- If the position is such that the vehicle can be recovered without becoming entangled, recover the vehicle to the TMS by using the underwater winch. Otherwise, follow the Entangled Vehicle procedures. If recovered using the underwater winch the vehicle will automatically latch onto the TMS as motive control and specific orientation are not required.

Instrument Failure

Computer Failure (where fitted)

- Enable the independent back-up control unit.
- Recover the vehicle in the normal manner.
- Where no back control is fitted, the ROV shall be recovered using the procedure detailed in the total hydraulic loss section above.

Total Loss of Instrument Power

Depending on the vehicles last known location and the structures and obstructions known to be between it and the TMS, the Supervisor shall decide whether to recover the vehicle using the Hydraulic Failure procedures or the Entangled Vehicle procedures.

Camera(s) or Sonar Failure

Camera(s)

All Video Signals - If all video signals are lost, sonar shall be used to provide location information and the vehicle shall be recovered by winching in the tether. Vehicle motive control shall only be used to maintain depth, provide constant tension on the tether, and to avoid entanglement or obstructions.

One or more camera remains operative - The situation shall be assessed to determine whether the work needs to be curtailed or abandoned. If the vehicle can safely maneuver and the task can be completed with the remaining camera(s) the work shall be continued, if not the vehicle shall be recovered.

Sonar

If the sonar is not required for the work and the visibility is great enough for navigating in the existing conditions, the task shall be continued; if not, the vehicle shall be recovered by winching in the tether if the visibility does not allow navigation.

Tether Separation

The Master of the Vessel (if operating from a vessel), or the OIM or Structure Supervisor/Manager (if working from a structure), shall be informed immediately. They shall be requested to notify all vessels in the vicinity to be on the lookout for the vehicle and to stay clear of the immediate area. The vehicle should float to the surface and the pinger beacon and strobe light will assist in its location. The TMS shall be recovered.

When the vehicle is located:

- It shall be monitored closely until a vessel with a lifting capability (5 tons) is available. A soft line can be attached and the vehicle towed by a small craft (rescue boat or inflatable) to a position where it can be lifted by a structure/vessel mounted crane.

- An ROV crew member shall be transferred to the recovery vessel with the vehicle's "Transit Lift Bracket".

- The ROV crew member shall then supervise attachment of the Transit Lift Bracket to the vehicle and the vehicle recovery onboard the vessel/structure. If the Transit Lift Bracket can not be fitted due to swell/wave action, a nylon strop capable of lifting the vehicle may be fitted to the vehicle lift point and "choked" in position.

- Transfer of the vehicle to the spread site shall be arranged.

Umbilical Separation (TMS System)

- All systems shall be immediately shut down and a fix obtained on the point where the TMS was lost.

- The Master of the Vessel (if operating from a vessel), or the OIM or Structure Supervisor/Manager (if working from a structure), shall be informed. They shall be requested to notify all vessels in the vicinity to be on the lookout for the vehicle and to stay clear of the immediate area.

- The ROV Operations Base shall be notified of the situation.

- Depending on the distance that the vehicle was from the TMS at the time of the separation, and the water depth, the vehicle may rise to the surface. If the vehicle is on the surface a soft line shall be attached to the vehicle and secured so that it does not suffer contact damage.

- An ROV crew member and the Transit Lifting Bracket shall be transferred to the recovery spread.

Recovery by ROV or Diver

Recovery by ROV

- With the recovery vessel standing well clear of the loss location, the Recovery ROV shall be used to locate and attach a marker to the vehicle.

- The Recovery ROV shall be used to locate and attach a marker to the TMS.

- The length of the tether shall be inspected to ensure that recovery operations will not cause the entanglement of the vehicle.

- Once the vehicle and TMS have been marked, the recovery vessel shall be moved into a position to recover the TMS. If the vehicle is on the surface, a small craft shall maintain slight tension on the vehicle in a direction away from the recovery vessel. Otherwise, the craft shall stand by to attach a soft line to the vehicle when it reaches the surface during the TMS recovery.

- The Recovery ROV shall be used to attach a lifting wire to the TMS; it shall then be recovered to the surface.

- The vehicle shall be brought to the side of the vessel by hauling in the tether (a capstan or power sheave with a minimum diameter less than 24 inches (610 mm) shall not be used).

- The Transit Lifting Bracket shall be attached to the vehicle and it shall be recovered onboard. If unable to attach the Transit Lifting Bracket due to swell/wave action a webbing strop, capable of lifting the vehicle, may be used. The strop shall be choked to the lifting point of the vehicle.

- The TMS, umbilical, tether and the vehicle shall be separated from each other and the four items and the Transit Lifting Bracket returned to the vehicle spread.

Recovery by Diver

The Client Representative, with assistance from the Supervisor, shall control all aspects of any recovery operation carried out by Divers.

- With the recovery vessel standing as far clear as possible from the last known location of the vehicle, the Diver shall locate the TMS and the vehicle making use of their pingers and strobes.

- The length of the tether shall be inspected to ensure that recovery operations will not cause entanglement of the vehicle.

- Once the vehicle and TMS have been marked, the recovery vessel shall be moved into a position to recover the TMS. If the vehicle is on the surface a small craft shall be used to maintain slight tension on the vehicle in a direction away from the recovery vessel. Otherwise, the craft shall stand by to attach a soft line to the vehicle when it reaches the surface during the TMS recovery.

- The Diver shall attach a lifting wire to the TMS for recovery to the surface.

- The vehicle shall be brought to the side of the vessel by hauling in the tether (a capstan or power sheave with a minimum diameter less than 24 in (610 mm) shall not be used).

- The Transit Lifting Bracket shall be attached to the vehicle and recovered onboard. If the Diver is unable to attach the Transit Lifting Bracket to the vehicle due to swell/wave action a webbing strop, capable of lifting the vehicle, may be used. The strop shall be choked to the lift point of the vehicle.

- The TMS, umbilical, tether and the vehicle shall be separated from each other and the four items and the Transit Lifting Bracket returned to the vehicle spread.

Umbilical Separation (Free Swimming Systems)

These procedures are basically the same as the procedures in the previous section.

Entangled Vehicle

An entanglement will become apparent by being visible or by the inability of the ROV to respond correctly to control commands.

Immediate Action

If the entanglement is not visible, the HPUs shall be shut down. Following this action, the thrusters will be inoperative and the ROV may ascend to the limit of the "free" tether. Close observation of the ROV's performance at this stage may allow deductions to be made as to the probable cause of entanglement. It is also possible that the ROV may free itself at this stage.

Subsequent Actions

- Switch **Depth Auto** mode to **OFF**.

- Switch **Heading Auto** mode to **OFF**.

- Set **all Trim functions** to **ZERO**.

- Enable HPU 1 (2) and conduct an all-round visual survey of the ROV using pan and tilt plus any other vehicle-mounted cameras. **The thrusters shall not be used.**

- If the entanglement is visible and does not inhibit the thrusters, the ROV shall be positioned to allow the manipulators (if fitted) to be used to release the snag.

Use of TMS (if fitted)

The tether may be wound in to the TMS, but only if the ROV/TMS orientation is simple and the tether is not located around structural members, pipelines, etc. This operation may release the vehicle.

Notification of Entanglement

- As soon as the Shift Supervisor is convinced that the ROV cannot be released by using self-help techniques, he shall inform the following personnel:

  - Client's Representative
  - ROV Superintendent
  - Company Base - ROV Operations Department

- The ROV's status shall then be permanently monitored, using instrument power only.

Recovery of ROV by Divers or another ROV

Preparation

The Superintendent shall prepare a sketch of the ROV/TMS/TETHER/UMBILICAL configuration, relative to the entanglement and surroundings (e.g. structure, bottom features, anchor wires, etc).

- If the entanglement is visible, but not releasable, this information shall be included.
- Estimated ROV buoyancy status shall be included.
- A copy of a drawing of the ROV shall be included. This drawing shall be marked with TMS attachment location (if fitted) and delicate instrument and exposed connector locations.

This sketch shall be passed to the Rescue Spread.

Recovery by ROV

- Instrument power shall remain Enabled and all subsea lights shall be at full power.
- The Rescue ROV shall locate and survey the trapped ROV.
- The Rescue ROV shall attempt to clear the entanglement.

- If this is successful, the previously trapped ROV shall enable HPUs 1 (2) and remain in the vicinity to allow the Rescue ROV to exit the site.

- The previously trapped ROV shall then be recovered to the deck.

Recovery by Diver

- The Client's Representative assisted by the ROV Supervisor shall control all aspects of any ROV rescue operation carried out by Divers.

- Prior to Divers entering the water, all power on the ROV, TMS and winch shall be DISABLED.

- The Diver shall clear all thrusters from entanglements and release the ROV.

- The Diver shall retire to a safe place and the ROV shall be informed when it is allowable to switch on the System Power.

- If the ROV is still incapable of recovery and is located within a Structure, the ROV Handling Latch or a webbing strop shall be passed to the Diving Spread.

  - The Recovery device shall be attached to a surface winch or crane and then the Diver shall attach it to the ROV.

  - If a webbing strop is used it shall be choked around the vehicle lift point.

- The Diver shall then maneuver the ROV to the outside of the structure/debris area using surface assistance as necessary.

- The TMS (if fitted) or winch shall be activated to reel in the slack tether or umbilical and the diver shall release the recovery device.

- The Diving Spread shall clear the site and the ROV shall be recovered.

- The Diving Spread shall return the recovery device to the ROV Spread.

TMS Failures

Instrument Failure

As the latch indicators are hard-wired to the surface, the only component to fail will be the camera. The camera is not an essential component on the TMS so its failure will not affect the operation, therefore the dive need not be terminated until the work is completed.

Hydraulic Failure

If the TMS HPU fails, the underwater winch is inoperative. Thus, the recovery of the ROV can not take place in the normal fashion and the following procedure shall be followed at the end of the dive. (NOTE: the dive need not be terminated for this failure unless there is an indication of water leakage into the TMS's components.)

- The ROV shall be positioned alongside the TMS and match its ascent to the surface. As the ROV ascends it shall be maneuvered away from the structure/vessel.
- When the TMS is clear of the water, the ROV shall be positioned and held, on the surface, below the TMS. If the tether becomes tight during the TMS recovery, the relief valve on the underwater winch will release and tether will pay out.
- Once the TMS is on deck, it shall be repaired as rapidly as possible for normal recovery of the vehicle. If it can not be repaired rapidly, or the sea or other conditions make it essential for the vehicle to be recovered, the tether shall be routed so that the vehicle can be manually latched when the TMS is returned to the splash zone.

Winch Failure

Winch Failure during Launch or Recovery - TMS and Vehicle Underwater

- If the deck winch fails during a dive the vehicle shall remain mated to the TMS.
- The LARS shall be secured to avoid excess strain on it while the winch is repaired.

Winch Failure during Launch or Recovery - TMS and Vehicle In-Air

- If the failure occurs while the load is in the air the TMS assembly shall be secured in such a fashion as to prevent contact damage with the structure or vessel.
- The LARS shall be secured in such a fashion as to avoid excess strain on it while the winch is repaired.

Power Supply Failure

In the event of power failure during a dive, the system will become inoperative and the ROV will float up to the level allowed by the "free" tether and the surrounding conditions. This may mean that it reaches a depth shallow enough to be endangered by vessel movements. Immediately notify:

- The Master of the Vessel, when working from a vessel, providing the approximate location of the vehicle.
- The OIM or other person in-charge of the structure being worked from so they can inform shipping in the area.

Once power is restored

- Determine the vehicle's location using the onboard cameras and sonar.
- Return to and mate with the TMS.
- Conduct an in-water check of all systems and assess any damage before making a decision to continue with the work.

Maintenance

The maintenance schedules for all parts of the System comprise the remainder of this Section.

Maintenance work shall be performed in accordance with these schedules and the Vehicle Manufacturer's Maintenance Manual. All the checks and actions specified in the following checklists should be carried out daily, unless specified otherwise on the checklists. On completion of the maintenance carried out offshore, a statement shall be recorded on the Maintenance Log Sheet, ROV Daily Telex Report and The Remote Vehicle Daily Report.

All equipment shall be suitably labelled to indicate its operational status on arrival at the ROV Operational Base, in accordance with Company Procedures.

ROUTINE MAINTENANCE - VEHICLE

MAINTENANCE ACTION	ACCEPT/REJECT CRITERIA	CHECK EVERY		
		DAY	WEEK	MONTH
Check wires, cables and hoses for wear and damage.		*		
Check for loose or missing hardware. Repair or replace as necessary.		*		
Check sacrificial anodes for deterioration.	Replace when 50% depleted	*		
Check for corrosion. Apply protective coatings as required.		*		
Check motor and stator compensator level on HPUs.	See compensator adjustment procedure	*		
Check for an accumulation of sediment or other material behind motor and stator compensators. Clean out thoroughly.		*		
Check hydraulic compensator level. Add oil or bleed as required.		*		
Check condition of hydraulic system oil through sight glass.		*		
Check auxiliary compensator levels. Add oil or bleed as required.		*		
Check for water intrusion in electrical equipment compensation systems.		*		
Check motor/pump adapter housing fluid level.		*		
NOTE: Failure to keep the proper fluid level in the motor/pump adapter housing will result in **serious** damage to the motors.				
Check for leaks in hydraulic and pressure compensation systems.		*		
(Continued overleaf)				

ROUTINE MAINTENANCE - VEHICLE (CONTINUED)

MAINTENANCE ACTION	ACCEPT/REJECT CRITERIA	CHECK EVERY		
		DAY	WEEK	MONTH
Check hydraulic lines at pumps for loose connections.		*		
Check power supply to ground fault detection system.		*		
Check for water in hydraulic fluid.			*	
Lubricate lift-point rotating surfaces with Aqualube.			*	
Vacuum test on power and control cans.				*
High voltage isolation with megger.				*
Perform safety ground test.				*
NOTES: (1) Or before and after each dive, whichever is more frequent				

ROUTINE MAINTENANCE - TMS

MAINTENANCE ACTION	ACCEPT/REJECT CRITERIA	CHECK EVERY		
		DAY	WEEK	MONTH
Check wires and cables for wear and damage		*		
Check for loose or missing hardware		*		
Check sacrificial anodes for deterioration	50% depletion	*		
Check for damaged padding and bumpers		*		
Check for corrosion. Apply appropriate corrosion protection		*		
Check system oil compensator level - both hydraulic and electrical equipment		*		
Check motor compensator level		*		
Check for an accumulation of sediment behind motor compensator diaphragm. Clean areas as required. **DO NOT** remove the plastic diaphragm cover**!**		*		
Check level of fluid in motor/pump adapter. **NOTE**: Low fluid level can cause serious damage to the electric motor**!**		*		
Check hydraulic and compensation systems for leaks or loose fittings		*		
Check chains for tension		*		
Lubricate lubrication points		*		
Check tether for wear or damage		*		
Check condition of Cog Wheels		*		

ROUTINE MAINTENANCE - TMS (CONTINUED)

MAINTENANCE ACTION	ACCEPT/REJECT CRITERIA	CHECK EVERY		
		DAY	WEEK	MONTH
Check hydraulic system oil for water	Flush if any water is present		*	
Check idler pulley tension			*	
Check bearings for wear			*	
Check tether guide rollers for wear			*	
Check electrical system for water	Flush if water is found		*	
Check tether length - consult Tether Log Sheet	Replace if less than 60m			*
Lubricate Docking Con Rotator, check for wear				*
Inspect and lubricate bearings				(2)
Lubricate rollers				(2)
Lubricate latching solenoid mechanism.			*	
NOTES: (1) Or before and after each dive, whichever is more frequent. (2) Every 6 months.				

ROUTINE MAINTENANCE - SURFACE CONTROL MODULES

MAINTENANCE ACTION	ACCEPT/REJECT CRITERIA	CHECK EVERY		
		DAY	WEEK	MONTH
Visual inspection of cabling.	Damaged insulation or apparent strain			(2)
Visual inspection of connectors for loose casings, pottings, cleanliness, and water resistance.	Cracked casings, bent pins, stripped threads or damaged 'O' rings			(2)
Visual inspection of components in consoles for loose mounting hardware, etc.	Physical damage to wiring harness or components			(2)
Check toggle switches for ease of movement.				(2)
Check that front panel fuses are in place and correct.	Incorrect amperage ratings			(2)
Clean connections with approved solvent.				(3)
NOTES: (1) Or before each dive, whichever is more frequent. (2) Before mobilisation of system (prior to departure) and (3) Before mating connectors				

ROUTINE MAINTENANCE - WINCH

MAINTENANCE ACTION	ACCEPT/REJECT CRITERIA	CHECK EVERY		
		DAY	WEEK	MONTH
Grease drum bearing		*		
Grease levelwind horizontal guide roller		*		
Grease levelwind vertical guide rollers		*		
Grease levelwind guide wheel		*		
Grease levelwind drive gear		*		
Grease levelwind arm cylinder pins			*	
Grease levelwind arm trunnions			*	
Grease levelwind roller arm shaft			*	
Lubricate levelwind clevis and link pins			*	
Grease levelwind slide bearings			*	
Change oil in drum reducer and drum brake				*
Change oil in levelwind worm gear box				*
NOTES:(1) Or before and after each dive, whichever is more frequent.				

ROUTINE MAINTENANCE - "A" FRAME

MAINTENANCE ACTION	ACCEPT/REJECT CRITERIA	CHECK EVERY		
		DAY	WEEK	MONTH
Grease link pins			*	
Grease boom pivot			*	
Grease boom cylinder rod end eye and base end pin			*	
Grease damping cylinder base end eye			*	
Grease damping cylinder arm			*	
Grease swing frame pivot tube			*	
Grease swing frame upper and lower sheave arm bearings			*	
Grease swing frame sheave pin			*	
Grease swing frame lock plate pivot				*
Lubricate swing frame lock cylinder pins				*
Grease swing frame orbit pivot				*
Grease swing frame orbit plate thrust face and ring/pinion				*
NOTES: (1) Or before and after each dive, whichever is more frequent				

DOCUMENTATION OF ROV OPERATIONS

Introduction

Oceaneering maintains a structured procedural approach at all levels of its business including documentation. This section provides a sample of their documentation procedures and requirements used for the start up and ongoing running of ROV operations.

Company Documents

Company Documents Used Offshore

The documentation in use offshore includes:

- Daily Operations Report
- Dive Log Sheet
- Pre/Post Dive Checklist
- Telex Report
- Video/Photolog Sheet
- Maintenance Log
- Equipment Movement Order (EMO)
- Material Requisition

All forms, reports and video commentaries shall be completed in English unless the Client requires a different reporting language.

Frequency of Document Use

The following documents shall be used during each dive, if required:

- Pre/Post Dive Checklist
- Dive Log Sheet(s)
- Video/Photo Log Sheet(s)

The following documents shall be completed on a daily basis:

- Daily Operations Report

The following documentation shall be completed as required:

- Telex Report
- Maintenance Form

The Equipment Movement Order (EMO) shall be completed each time materials are transferred between vehicles or shipped to/from shore.

The Materials Requisition shall be completed each time an order is placed, whether it is by phone/radio or telex/fax.

Dive Checklists

Dive checklists appropriate to the vehicle configuration and the operation/project requirements shall be provided at the start of the project and replenished as required.

Pre Dive Checks

The Checklist shall be prepared by the Pilot with the assistance of other crew members as required.

On completion of the Checklist, the Pilot shall enter into the Dive Log that the pre dive checks are complete.

Post Dive Checks

On completion of the dive the Pilot shall go through the Checklist again.

He shall ensure that any discrepancies are noted and that the Supervisor is made aware of them so that correct maintenance/repair can be performed.

On completion of the post dive checks, the Pilot shall enter into the Dive Log that the Post Dive checks have been completed.

Dive Logs

The Dive Log shall be used for recording all details of the dive. A "scratch sheet" shall not be used. All sections shall be completed.

Completion of Dive Logs

The majority of the times on the Dive Log sheet are self-explanatory, but the following items are necessary as a minimum aid in its correct completion. If any section of the Dive Log are not applicable they shall be annotated "N/A".

Dive Number

The dive number shall start with '1' and increase for the duration of the project/contract. Separate numbering systems shall not be used for different vehicles on the same project unless they are in different locations (e.g. separate vessels or platforms).

Vehicle

Include the type and serial number.

Job Number

This shall be the Company ROV Job Number assigned specifically for the project and the subject vehicle only. Additional vehicles on the same project shall be assigned another in the sequence.

Positions

Personnel may have more than one function, or several members of the Crew may perform the same function during the course of a dive (particularly Pilot). They shall be listed in the space available in the order in which they fill the position. Changes in Supervisor, Pilot and Observer/Inspector shall be logged as an event and the time of change recorded. If a video recording is being made, such changes shall be recorded (audio) there as well.

Client

This information shall be provided to the Senior Supervisor/Superintendent during mobilization and shall be used on all documents relating to the contract.

Client's Representative

The name of the Client's Representative directly responsible for the ROV operations shall be entered here (signature is not required).

Sea State

This shall be estimated from the conditions and given as a range over the course of the dive.

Wind Speed

Enter as available from the vessel or platform. This shall be given as a range over the course of the dive and recorded in knots or m/sec (indicated)

Underwater Conditions

- Max - Is the maximum depth reached during the course of the dive, not the seabed depth.
- Current and Visibility - Shall be logged for the work site.

Dive Task

This shall be a detailed description of the tasks to be completed during the dive.

Event

These shall be items of significance that take place during the course of the dive and shall include, but not be limited to:

- Start and completion of pre-dive, in-water, and post-dive checks;
- Any reportable items from those checks;
- Vehicle off deck, in-water, released from TMS, at work location, start and completion of work, off location, mating with TMS, at surface, on deck;
- Important observations during the dive (navigation fixes, damage or discrepancies to items being inspected or observed, results of measurements, etc.);
- Changes of crew, task, reasons for leaving/abandoning task, changes in equipment status.

Time

Local time on the basis of a 24-hour clock shall be used.

Continuation Sheets

The header needs to be filled out in full only on the first sheet of a multiple sheet dive. The second and subsequent sheets shall have the Dive No., Date, Job No. and Page information filled in.

Video/Photo Log Sheets

This log shall be kept when a video tape is being made of any or all of a particular dive or when photographs (slides or prints) are being taken. A separate log shall be kept for each still camera fitted to the vehicle and video and photographic logs shall be kept on separate sheets.

Completion of Video/Photo Logs

Log No*.*

This follows the same procedure as for Dive Number, being incremented for each tape or roll of film used on a project.

Tape Run Number

This shall be taken from the video tape machine, so care must be taken to reset the counter at the start of each new tape. It provides an approximate location point for finding the subject.

Still Number

This shall begin with '1' for each new roll of photographic film. On dives where the roll of film is not new the numbers shall be continuous with the previous photo log (taking into account any on-deck trial shots).

Event/Subject

In addition to obvious important images (damage, close inspection, etc.) it shall note:

- Any breaks in the recording
- Changes of camera being recorded
- Changes in Pilot and/or Observer/Inspector
- Navigational fix number as provided by the Surveyor
- For still cameras the type of film (color or black and white, slide or negative, and the ASA rating)
- The Dive Number. This shall also be included as an overlay on the video recording.

F-stop and Distance

These are the camera settings, made on the surface, (distance in meters) unless these can be varied remotely during the dive. In that event, those details shall be included with the subject information.

Distribution of Copies

Video/Photo Logs shall be distributed as follows:

- One is retained with the video tape or roll of film
- One may be given to the Client on site
- One to be retained onboard in Job file
- One to be sent directly to the ROV Department for Job File

Daily Operations Report

The Daily Operations Report contained information used in preparing the invoices to the Client. It is very important that the information it contains is accurate and that the Client's Representative agrees with it and signs it.

Completion of Daily Operations Report

In the completion of the Daily Operations Report the following definitions apply:

Personnel

These are the total number of the ROV Crew in each category onboard at 2400 hours on the day of the report.

Times

All times shall be recorded for the period 0001 to 2400 in minutes. These are to be agreed with the Client's Representative.

Available

The time that the Spread was available for work. If individual items were on Breakdown they do not affect this time unless they prohibited the Work from being conducted.

Idle

The amount of time during which there was insufficient crew available for a dive to be conducted (e.g. during the "maintenance shift" or if the entire crew takes a meal break, etc.).

WOW - Waiting on Weather

The time that the spread is unable to operate or would be unable to operate due to weather conditions. If other downtimes are in effect they shall have priority and WOW shall not be considered to be in effect.

Waiting on Priorities

This is time spent waiting for operations by the Client or other Contractors to be completed, clearing the area or allowing Company operations to be conducted safely in conjunction with the Clients.

In-Water

The total of the times that the vehicle was in the water (recorded from TMS or vehicle entry into the water until the TMS or vehicle is lifted clear of the water).

Working Time

The total of the time that the vehicle was on the work site (recorded from the vehicle's arrival at the work site–within one minute–to its departure from the site). This may be modified to match individual Client's requirements and an agreed definition will be issued to the Supervisor.

Transfer Time

The total of the times from when the vehicle lifts off the deck until Working Time starts, and then from the completion of Working Time until the vehicle reaches a new worksite or until it is on deck.

Preparation

The time spent on-deck, by the ROV crew (not the total of the individuals' times but the period involved), in pre and post dive checks and in setting up equipment (whether the equipment is Company or Client supplied).

In-Water Checks

The total of the times spent on in-water checks prior to release from the TMS (or starting for the worksite on vehicles without a cage/TMS).

Breakdown

The time that the spread is on breakdown. Refer to the contract notes issued by ROV Operations Department i.e. the time runs from the time that the vehicle leaves the worksite (if that is where the breakdown occurs) and return to the worksite provided other priorities or downtimes (e.g. weather, vessel movements, etc.) do not interfere with such a return or demonstration of availability.

Relocation

The time that the vessel spends relocating within the particular field. If working from a structure, this is the time that it takes to change spread locations on the structure or move to another structure within the same field.

Port

This is the time that the support vessel is in port, from mooring to unmooring.

Transit

The time travelling from harbor to work location or between fields, but not the time moving between sites within one field.

Other

Time spent on anything other than those items already listed.

Time

In the WORK DESCRIPTION section, this refers to the time of day, on a 24-hour basis, not the amount of time spend doing something.

Work Description

The items to record here are significant events in the day:

- Start and completion of dives
- Crew changes
- When items break down and when they are repaired
- Start and completion of maintenance periods and the items that were maintained
- Work done on each dive
- Amount of that work completed
- Accidents, injuries, near misses etc.

Personnel

- **Name** - The name and position of the person shall be entered into this space.

- **Arr** - Arrival - tick this box if the person arrives this calendar day.

- **Dep** - Depart - tick this box if the person departs this calendar day.

- **Days** - The number of days the person is onboard, including the day of arrival and day of departure.

Equipment

- **Quantity** - The quantity of a particular item.

- **Reference** - The contractual reference number or the reference number of the request to add the item to the dayrate list.

- **Item** - A brief description of the item (e.g. CH-3 system, Krautkramer DMU, etc.)

- **Avail** - The number of hours that the item was available for work, including working time.

- **Stdby** - The time that the equipment was on-hire at the Standby Rate. The Supervisor shall be notified by the ROV Operations Department or at the time that the Client makes a request for a dive (not the start of the dive itself).

- **Bdwn** - This is the time that the item was "broken". The Supervisor shall not deduct any contractual allowance. This category is cumulative if the item breaks down more than once in the period 0001 - 2400.

- **Mob/Demob** - The time spent mobilising or demobilising the equipment. Note that the Work Description section shall show the start and finish times.

Consumables

The Supervisor shall be provided with a list of items or categories of items that are considered consumables under the particular contract.

The Supervisor shall list all consumables used each day. He shall also list any items that he thinks may be considered consumable and also such items (such as hydraulic oil) that are consumed, but are not a contractual consumable, so that their use can be monitored and new supplies sent as required.

- **Quantity** - The number or amount of the item used, consumed or provided to the Client or other Contractors.

- **Reference** - The contractual reference number or the reference number of the request to add the item to the consumable list

- **Description** - This shall allow accurate identification of the item used.

Damage to Spread

If any damage has been sustained by the Spread, however caused, the answer YES shall be ticked and the ROV Operations Department notified. In addition, a damage report shall be completed indicating the extent of the damage and how it was sustained. Relevant persons, including the Client's Representative shall sign the report.

Maintenance

Pilot - Maintenance Checklist

The Pilot in charge of the ROV shall ensure that all of the required checks have been carried out according to the maintenance schedule provided in the relevant System's Operating Procedure and the Vehicle Manufacturer's Maintenance Manual. Any defects are to be rectified or recorded, before signing the Dive Log, giving the ROV clearance to proceed with the dive. The ROV Supervisor shall check the list and ensure that it is correct.

Pilot Pre and Post Dive Checklists

These checklists are not intended to remove any responsibility from the Technicians regarding maintenance. The Pre Dive Checklist is intended to ready the ROV for launching and to ensure that none of the systems have been interfered with after the Technician has completed his maintenance.

The Pilot shall complete all checks and note on the Dive Log that checks have been completed and that he is satisfied that the ROV is ready to dive.

The ROV Supervisor shall check that the pre dive checklists have been completed before giving clearance to dive.

The post dive checklist is intended to ensure that the Pilot is aware of the condition of the ROV after the dive and to ensure that all known defects are reported to the ROV Supervisor and the Maintenance Technicians.

Maintenance of the Spread

Full documentation shall be supplied with each spread. This documentation is divided into three main areas:

- Operations and Maintenance Manuals and Drawings.
- Suppliers Manuals and Drawings.
- Catalogues of Equipment

All of these documents shall be kept in a tidy and useable condition. If pages are removed, they shall be correctly replaced by the ROV Department.

Maintenance shall be conducted in accordance with the Company and Manufacturers recommended practices.

ROV Maintenance Checklist

The Pre Dive Checklists are only valid for the dive in hand, although it is left to the Supervisor's discretion to decide whether or not a dive is terminated.

ROV Maintenance Schedule

All maintenance shall be carried out and documented in accordance with the maintenance schedule provided in the relevant System's Operating Procedure and the Vehicle Manufacturer's Maintenance Manual. The checks are required to be completed on a daily, weekly, monthly basis or after a specified number of running hours and shall be recorded on the following documents:

- Maintenance Log Sheet
- Daily Telex Report
- Remote Vehicle Daily Report

Maintenance Log Sheet

The purpose of a Maintenance Log Sheet is to record that the maintenance work is carried out and its completion indicated by the initials or signature of the responsible person. In addition, the required installation shall be recorded weekly on the Maintenance Log Sheet. All materials used shall be recorded separately in order to maintain stock control.

- **Offshore** - The Maintenance Log Sheet shall be completed on a daily basis.

- **Onshore** - During mobilizations and refurbishments, the Maintenance Log Sheet shall be augmented by a Maintenance Log, completed by each team member covering their individual input to the project.

TELEX Report

The Telex Report is used to provide a standard report to the local office to allow continual monitoring of the progress of the Work and the requirements of each location. If the location does not have a telex facility, the details should be faxed if possible or phoned to the office as early as possible during normal working hours.

Equipment Movement Order

All items being returned from an offshore location must be covered by an Equipment Movement Order (EMO) which shall be completed by the System Supervisor or other competent.

Identification of Equipment

All equipment being returned from offshore shall be either red or green tagged dependent on condition. This tag shall contain enough information to completely identify the equipment, i.e. description, part number, serial number, whether it is faulty or serviceable, the system identity, the Technician's name and the date.

Equipment Asset Numbers

All Oceaneering's equipment is clearly identifiable by a unique "asset number". Where the "asset number" is known it is imperative that it is quoted on all EMO's and ID tags. These asset numbers have been introduced to simplify and tighten-up the stock control system.

Demobilization of ROV Spreads to Base Inventory

The movement of complete ROV spreads at the end of a contract shall be covered by an Equipment Movement Order (EMO). This EMO shall be completed in the same manner as the movement of equipment to Base from Offshore.

Material Requisitions

All materials ordered for a system, whether onshore, during mobilization, offshore or during demobilization shall be placed on a Material Requisition Form. The purpose of the Offshore Materials Requisition Form is to:

- Avoid duplication of orders
- Provide an easy method of tracking the status of the request, both offshore and onshore
- Obtain onshore review and authorization prior to any purchasing commitment being made.

Indemnification Agreement

This agreement confirms that Client shall indemnify, hold harmless and defend Company for loss, damage and liability in respect of operating unmanned ROV systems in conditions of bad weather, dangerous situations or environmental hazards, such as blowouts, which are outside terms of the Contract and/or expose the equipment to loss or damage by extending the operation of the equipment beyond the operating limits.

SAFETY OF ROV OPERATIONS

Safety Policy

The management must hold in high regard the safety, welfare, and health of all its employees.

Production is not so urgent that we cannot take time to do our work safely.

In recognition of this, one must constantly work toward:

- The maintenance of safe and healthful working conditions.
- Consistent adherence to proper operational practices and procedures designed to prevent injury and illness. The company will abide by the Operating and Maintenance Standards.
- Conscientious observance of all federal, state, local, and company safety rules.

It is wrong to believe that accidents are unavoidable and will always happen. If all of us do our part, including acting and talking safety at all times, a healthy attitude toward accident prevention and an improved safety record can be achieved.

Additionally, management and all employees must be alert to avoid the possible occurrence of accidents to property and equipment of the company and to any non-company owned property and equipment. This also includes preventing the possibility of accidental injury to members of the general public, contractors, and/or clients, whether on company property or theirs.

Reducing accidents and related insurance costs will permit the company to be more competitive in the industry, thus helping to safeguard jobs.

Operating Standards

Safety

Personnel safety is always the primary consideration and will not be compromised.

Customer Communications and Expectations

Before and during each significant operation, consult with the Customer to:

- establish mutual expectations through appropriate communications in an atmosphere of cooperation

- develop a thorough understanding of the upcoming program and the duties and obligations of everyone involved

- reach agreement as to the Customer's expectations concerning the company's contribution

- devise plans that define and use, to best advantage, all available resources to complete the job safely, efficiently and in accordance with mutual expectations

Leadership and Teamwork

Operations are a team effort with direction and ultimate on-site accountability for results vested in the nominated company employee. When he deems it necessary, he may require individual participation that goes beyond assigned responsibilities.

Pride, Morale, Discipline

Personnel will receive sufficient training and supervision to:

- understand what is expected of them and become proficient in their jobs

- understand the relationship between individual performance and operating objectives

- understand the purpose and operation of all assigned equipment

- act as a team in performing the tasks necessary for efficient operations with skill and safety

- maintain, through personal appearance and conduct, a positive impression of morale, discipline, and pride

Measure Performance

Performance will be measured. Successful performance results in a job that is completed to mutual expectation in the most effective sequence without interruptions or surprises and in accordance with company operating procedures and policies. Always be prepared.

Review Results

Upon completion of a significant undertaking, company supervisory personnel will review the results with the Customer to determine whether or not expectations were met. Any variances in performance will be reviewed and appropriate action taken.

Equipment

Equipment will be properly operated and maintained in accordance with company published "Maintenance Standards".

Administration

Clerical administration will be current and completed to company requirements.

Maintenance Standards

Life Support and Safety Systems

All primary and secondary life support equipment and safety appliances will be fully operational 100 percent of the time. Safety equipment records will be maintained on a current basis.

Operating Knowledge

All operating personnel will understand equipment operation with regard to safety and efficiency.

Compliance

All equipment and devices covered by rules and regulations of all applicable regulatory bodies and classification societies are to be in compliance when in operational use.

Performance

Company owned or leased equipment will be maintained so that the performance levels will meet or exceed the operational requirements of the job.

Preventive Maintenance

Maintenance personnel will fully understand their responsibilities and carry out preventive maintenance on a scheduled basis. Equipment will be routinely serviced in accordance with manufacturer's approved schedules and instructions.

Repair Standards

Repairs of a temporary nature will be made permanent. Repaired equipment will be thoroughly tested to manufacturer's specifications prior to going on the next job.

Paint Standards

All paint on operational equipment will be maintained so as to provide adequate protection and present a professional appearance. Areas of corrosion are to be immediately inhibited, a protective coating applied, and repaired to specification at the earliest opportunity.

Administration

Maintenance records and reports will be kept current and accurate.

Introduction

The rules in this manual have been prepared for your protection, and are based on common safe practices and accumulated experience in the prevention of industrial accidents.

All company personnel are required to read and abide by all the safety rules contained in this manual. Your full cooperation in following and enforcing these rules will help provide a safe and healthy working environment for everyone. If you do not understand a safety rule in this manual see your supervisor. If this does not resolve the situation consult the Area Manager or Regional Safety Officer.

All accidents or injuries are to be reported by the job supervisor on the company’s "First Report of Injury to an Employee" form. The supervisor will sign the report. If the injured employee is the supervisor, the next most senior person will sign the report. All near miss incidents, or equipment failures, will be reported on the company "Near Miss/Equipment Failure/Malfunction Incident Report" form.

All UNSAFE conditions or acts must be reported to your Supervisor immediately. If conditions are not corrected, contact the Area Manager or Regional Safety Officer. Personnel will not be disciplined for reporting safety violations. The Regional Safety Officer will keep confidential the identity of anyone reporting UNSAFE acts or conditions.

Failure to comply with the Safety regulations outlined in this manual could be cause for disciplinary action up to and including termination without notice.

The safety rules in this manual are considered the minimum required by the company. All local and governmental laws and regulations for the area you are working in must be followed. Company operations manuals and technical reports describe procedures and requirements for diving operations, as well as safety rules. The ADS Operations Manuals, volume 1-4, detail specific safety requirements for ADS systems. Specific safety requirements and procedures are detailed in separate Safety Manuals used in specific operations and the manufacturers operating manuals for individual systems and components used by all divisions.

KNOW THE PROPER AND SAFE WAY, BEFORE OPERATING ANY EQUIPMENT

Safety Responsibilities

REMEMBER "Safety is Everyone's Responsibility"

Management

Management has the ultimate responsibility for formulating and maintaining an effective safety program. They are accountable to the President and CEO of the company to this end.

Supervisor

The Supervisor is responsible for and accountable to management for the following:

- They are directly responsible for maintaining safe working conditions and practices and for the safety of all employees working under their supervision.

- Each Supervisor is responsible for the proper orientation and training of the employees reporting to them. Job hazards and safety procedures should be fully explained to each employee before they begin work.

- It is also the Supervisor's responsibility to see that required personal protective equipment is used in accordance with safety rules and practices.

- Supervisors should encourage employee safety suggestions and give them immediate consideration.

- Supervisors will schedule department safety meetings as often as necessary to effect safe practices and work methods.

- They will investigate all accidents and near misses and prepare the company's "First Report of Injury to an Employee."

- Nowhere is the quality of supervision more apparent than in housekeeping. Good housekeeping is not only essential for safety, but is indicative of an efficient department.

Employees

Employees are responsible for exercising maximum care and good judgement in preventing accidents. They are responsible for reporting all injuries or illness to their

Supervisor. They are also responsible for reading and understanding the company Safety Manual, issued upon employment.

New Employee Orientation

A newly hired employee will fit one of three categories:

- First, a young person with little or no work experience who is probably totally ignorant of company business and work related situations.

- Second, the individual who has worked in various type jobs, some similar and others not similar.

- Third, the individual was hired because he or she is experienced in the work.

These three types have one thing in common, in varying degrees, as far as we are concerned - none are familiar with company operations and probably know very little about company work methods, tools, equipment, or policies and practices.

Therefore, it is important that each Supervisor not assume the new employee is ready to go to work until the employee is given some basic information and instruction.

To what degree this information and instruction is necessary depends in part on what the new employee's job will be. However, each supervisor should be sure to take whatever time is necessary to cover the basic policies and procedures, and any other information and instructions necessary to the job, specifically, the "Company Safety Manual".

Documented evidence of any such training/instruction should be made and placed in the new employee's file. Also, if additional training/instruction is given at a later date, this should be documented as well.

The attached "Safety Training" is a general guide that may be of assistance in accomplishing this training/instruction goal.

Safety Training

Studies show that 80 to 90 percent of all accidents involve unsafe acts. Obviously, the elimination of these unsafe acts will improve the company’s production and safety record. On-the-job instruction is most effective in teaching the worker the safe, efficient way to do the job. The Supervisor should conduct the safety training.

Before the Supervisor starts job instruction, determine which employees need the training most. These are some of the groups to be considered:

- Newly hired employees
- Transfers from other departments
- Accident repeaters;
- Those who have difficulty meeting production quotas or schedules

Get ready to teach before starting the job instruction:

- Break the job down into the important steps or operations, stressing the key points (safety is a key point)
- Have proper tools, materials and supplies available
- Arrange the workplace the way the worker should keep it.

Prepare the employee to learn:

- Put the employee at his ease, both physically and mentally
- Tell the employee what will be taught and find out what he knows about the subject
- Get the employee interested in what you will teach him
- Put the employee in the best position to see and learn (so he does not see the job backward, etc.)

Then present the operation:

- Take the important steps or operations one at a time
- Do the step while you tell about it--tell and show at the same time
- Explain the how and why of each operation. These are key points (stress safety)
- Instructions should be clear and complete. Repeat them as often as necessary

The employee should now ready to try the operation by himself:

- Have the employee do the operation and correct any errors immediately
- Have him repeat the operation, explaining the key points or the what or why of each step
- Have him repeat the operation until you are sure you know he understands
- Give the employee time to practice and develop the necessary speed and skill; let him develop confidence
- Check back to see if the employee needs help, and encourage him to ask questions
- Gradually taper off coaching and close follow-up, but let the employee know you are ready to help him at any time

If the employee has been thoroughly trained, all will benefit from:

- Increased production
- Reduction in waste
- Reduced labor turnover
- Improved safety record
- Improved quality
- Improved employee relations

REMEMBER -- if the pupil hasn't learned, the teacher hasn't taught.

Safety Meetings

Regular safety meetings are an important ingredient in any safety program. Meetings provide the vehicle for communications that are so vital in maintaining the exchange of ideas and information for controlling losses.

Regular safety meetings will be held at varying times for the different crews. Both employees and supervision are required to attend these scheduled meetings. Attendance will be taken and files maintained.

Meetings have but one goal - to help prevent accidents and injuries. Everyone's participation in these meetings is earnestly encouraged.

A "Safety Meeting Report" form or equivalent is to be completed for all safety meetings held, whether a group meeting, or a specially called meeting by a Supervisor for his crew. Safety meetings can also be documented on the daily job report logs. Have all attending sign the report, fill in subject matter and any suggestions by employees. Date, sign and return to the Operations Manager or Regional Safety Office.

Job Hazard Reviews are an effective tool to identify specific hazards on any type of job. A simple form with as many additional pages as required will help each employee understand the specific steps required for each task, the possible hazards involved, and ways to eliminate or reduce that hazard. Participation by all personnel in completing a Job Hazard Review will lead to a safer more efficient job.

General Safety and Rules of Conduct

Your employment may require hard physical labor and will expose you to hazards normal to the industry.

"Accidents Don't Happen--------They Are Caused"

All employees must follow the following general rules:

- You are responsible for keeping yourself in good physical condition. Each employee must be able to perform the essential job functions for their job description.
  - A Pre-Employment physical, by a company-approved doctor, is required for all offshore personnel.
  - Periodic (annual) physicals are required for some job descriptions.
  - Employees shall not attempt to work when ill or in any other unfit condition that may jeopardize the safety of themselves or others.
  - Employees must notify supervisors if taking medication that may affect mental or physical alertness, or if they become sick while on duty.
  - Employees must report all injuries to their supervisors, no matter how INSIGNIFICANT they may seem. Get First Aid treatment IMMEDIATELY.
- The use, possession, transportation, or sale of firearms, weapons, explosives, illegal drugs, intoxicating beverages, or other contraband on company property, boats, barges, or vehicles is grounds for immediate dismissal. Management may make unannounced and/or random searches of personnel, baggage, vehicles, desks, and work areas
- Fighting or horseplay will not be tolerated
- Employees shall maintain a clean work site
- Smoking is allowed only in designated areas
- Observe and obey all posted warning signs
- Report all unsafe conditions or practices to your supervisor

First Aid

All Offshore personnel should be trained in basic First Aid and CPR.

The company will provide basic First Aid Kits on all Installations and job sites where required.

Advanced emergency First Aid Kits are supplied to trained emergency medical personnel.

- Inventories and Logs of these kits are the responsibility of the Supervisor and Emergency Medical Technician/Diver Medical Technician (EMT/DMT).
- Drugs or IV's are to be administered only under the direct authorization of a doctor.
- EMT Kits are to be kept locked and in a secure place when not in the possession of a qualified EMT or Supervisor.

Basic First Aid procedures are detailed in Operations Manual Volume I and the Diving Emergencies Medical Handbook. A basic First Aid Manual must be on every job site.

Designated EMT/DMTs and/or appointed First Responders will be trained and offered a vaccination series in accordance with the company's Bloodborne Pathogens Program.

Any employee exposed to blood or other bodily fluids on the job must report that exposure immediately. All blood or bodily fluids are to be cleaned up using approved procedures and the contaminated materials sent in to the office for proper disposal.

Personal Protective Equipment

- Approved hard hats and safety shoes are to be worn in all shop and industrial areas by employees who work in or regularly visit these areas. Hard hats will not be modified or altered in any way that would effect the function of the equipment.
- Employees are required to wear suitable clothing for the type of work they are engaged in.
- Protective clothing, smocks, aprons, and safety glasses will be provided by the company for those who require them.
- Employees must wear the required protective equipment, as directed by management, for the type of work in which they are engaged.

- Respirators or earmuffs will be worn where required. Personnel required to work in respirators will receive the appropriate training before commencing work.
- Gloves or other hand protection shall be worn or used when required to prevent injury.
- Long hair or excessive facial hair will be contained when necessary to guard against fire hazards and rotating machinery hazards.
- Facial hair must not inhibit the effectiveness of Respiratory Equipment.
- Clothing shall be worn to protect against sunburn.
- Impact-type goggles or face shields must be worn when chipping, grinding, buffing, or hammering or any activity that may involve flying particles.
- Approved shields and lens will be worn when burning metal.
- Approved welding helmets fitted with shade lenses will be worn when welding.
- Open toe and/or heel shoes are strictly forbidden in all shop or industrial areas.
- Office Personnel or Visitors entering other work areas shall wear the required protective clothing and equipment for that area, as directed by Management.
- All Personnel Protective Equipment will meet the appropriate classification or specification for the type of work being performed.

Boat safety

- Passengers aboard boats will follow established safety rules and obey all instructions given by the boat captain.
- Ensure the vessel is rated for the number of passengers aboard.
- Check with the boat dispatcher and captain and sign the ship’s manifest if required.
- Ensure the boat has enough personal flotation devices for each crewmember and passenger.
- Know the location of life jackets, fire-fighting equipment, life rafts, and exits aboard the vessel.

- Know the alarm signals.
- Know what to do and where to go in different emergency situations.
- Passengers should remain inside the cabin while the vessel is underway.
- Observe all safety requirements when embarking or disembarking from a vessel.
- Know how to disembark from a vessel by use of a personnel basket or a swing rope.
- Personnel Flotation Devices are required to be worn on certain jobs. Check with your Supervisor before going Offshore.
- No personnel are to board or disembark from a vessel until directed by the vessel captain, or the vessel is safety and securely moored to a structure.

Helicopter Safety

- Stay off the helipad during take offs and landings.
- Do not approach the helicopter unless told to do so by the dispatcher or pilot.
- Always approach and depart from the side of the helicopter. The main rotor may dip to within 4 feet of the ground. Never walk around or under the tail of a helicopter.
- Store all baggage and/or equipment as directed by the aircraft pilot.
- Wear a life jacket and/or survival equipment as directed by the pilot.
- Keep seat belts fastened at all times.
- No smoking during take off or landing.
- Hats and other loose objects must be held securely when under the rotor blades.
- Bear in mind that the main rotor blades can dip to less than 6 feet from ground or deck level.
- Sign the flight manifest as directed by the dispatcher or pilot.
- Personal and baggage weight must be logged.

- Know the location of life rafts, survival equipment, and exits aboard the aircraft.
- Obey all instructions from the pilot.
- Deplane only when instructed by the pilot.
- Don't lift objects higher than your waist while under the rotor. Keep long object in a horizontal position.
- Keep the helipad clear of loose objects.

Offshore Platforms and Vessels

- When first coming on board an offshore platform or vessel, notify the person in charge and sign the manifest as directed. Request a site-specific briefing for that location.
- Read ALL safety and emergency instructions.
- Know the alarm signals.
- Know what to do and where to go in different emergency situations.
- Know the location of emergency and survival equipment and emergency exits in your area.
- Obey all posted rules and regulations.
- Know how to board a vessel from the platform using a personnel basket or swing rope. DO NOT attempt to transfer by this method until you have been instructed in the proper technique.
- Certain jobs will require the use of Personnel Flotation Devices and fall protection. Whenever working from a high place or over open water, check with your Supervisor for the correct Safety Equipment that will be needed.
- The company, as well as the client, strictly prohibits recreational swimming from a platform or vessel.

Rigging Safety

There are several special rules that govern the use of equipment required for hoisting operations. Hoisting equipment can be very hazardous unless it is used properly.

REMEMBER: "A Chain Is Only As Strong As Its Weakest Link"

- Do Not use any rigging equipment that does not have the load rating identified on the equipment.
- Some rigging equipment must be inspected periodically and the results recorded and filed.
- Cable clips shall only be installed in accordance with established standards, when approved for specific types of rigging.
- The weight of the load shall be determined to select the proper size of rigging.
- Sharp edges of the load to be rigged shall be protected to prevent damaging the rigging and creating a hazard.
- Tag lines shall be used when hoisting and rigging loads.
- Material or equipment rigging shall not be rigged from structural points that are unstable (such as handrails or conduit).
- Chains, ropes, slings, and hooks shall be inspected before each use. Damaged rigging equipment must be removed from service and disposed of.
- Do not suspend loads over employees.
- Employees shall not work under suspended loads.
- Use the appropriate charts, or the one found in the "Handbook for Riggers," to determine the correct rigging for the job.

Slings are used with other material handling equipment for moving material by hoisting. The types of slings are those made from alloy steel chain, wire rope, metal mesh, natural or synthetic fiber rope and synthetic web. All slings must have a tag or other identification specifying the maximum allowable working rating for that piece of equipment. The following applies to the use of slings during rigging:

Daily Visual Inspections

Each day before using, inspect slings, all fastenings and attachments for damage or defects. Damaged or defective slings are to be removed from service at once.

Chain Slings

Inspect each link for the following:

- Twists or bends
- Nicks or gouges
- Excessive wear at bearings points
- Distorted or damaged master links, coupling links, or attachments.

Wire Rope Slings

Inspect for the following defects or damage:

- Ten randomly distributed broken wires in one rope lay, or five broken wires in one strand in one rope lay.
- Wear or scraping of one-third the original diameter of outside individual wires.
- Kinking, crushing, bird caging or any other damage resulting in distortion of the wire rope structure.
- Evidence of heat damage, end attachments that are cracked, deformed or worn.
- Corrosion of the rope or end attachments.

Natural or Synthetic Fiber Rope Slings

Inspect for the following conditions:

- Abnormal wear
- Powdered fiber between strands
- Broken or cut fibers
- Variations in the size or roundness of strands
- Discoloration or rotting
- Distortion of hardware in the sling

Synthetic Web Slings

Inspect for the following conditions:

- Acid or caustic burns
- Melting or charring of any part of the sling surface
- Snag punctures, tears or cuts
- Broken or worn stitches
- Distortion of fittings

Hooks

Slings and hooks, or hooks only should be removed from service if hooks are cracked, have been opened more than 15 percent of the normal throat opening measured at the narrowest point or twisted more than 10 degrees from the plane of the unbent hook.

Cranes, Hoists and Forklifts

Periodic inspections of mobile cranes, hoists, and forklifts are required. The results of the inspections must be recorded and filed.

Operations of cranes, hoists, and forklifts:

- Only trained, qualified operators shall be designated in writing by the person in charge. All personnel performing the duties of the rigger during hoisting and lifting operations will be trained.

- Trainees will operate the equipment only under the direct supervision of a designated operator.

- Maintenance Personnel and Inspectors may operate the equipment when necessary in the performance of their duties.

Safety:

- The operator shall receive and act on hand signals from only one signalman at any time.

  - The operator should obey any emergency stop signal given.
  - Standard signals for the industry should be used.

- Mobile cranes and forklifts shall be equipped with an audible backing device, in operable condition, with appropriate signs posted.

- Loads shall not be moved above employees, nor shall employees walk or work under a suspended load.

- Do Not ride the load, hook, or headache ball. Employees may only be moved by use of approved personnel basket or net.

- Use tag lines with all loads.

- There shall always be at least two complete wraps of cable left on the drum during operation.

- If the operator considers a load unsafe to lift, the operator MUST refuse to make such a lift.

- The operator is responsible for the safe operation of his equipment.

- NEVER exceed the safe working load of any component of the lifting equipment.

Cranes and Hoists

An inspection of the critical parts of cranes and hoists is required on a monthly basis. Listed below are those parts and components of cranes/hoists that should be inspected. Obviously, not all cranes or hoists have all the parts and components listed, so it would not be necessary to include all of the following on an inspection report.

Those items to be inspected are:

- Hooks for deformation or cracks.
- Hoist or load attachment chains, including end connections, for excessive wear, twist, distorted links interfering with proper function, or stretch beyond manufacturer's recommendations.
- Wire ropes and rope slings, including end connections, for excessive wear, broken wires, stretch, kinking or twisting.
- Deformed, cracked, or corroded members.
- Loose bolts or rivets.
- Cracked or worn sheaves and drums.
- Worn, cracked or distorted parts such as pins, bearings, shafts, gears, rollers, locking and clamping devices.
- Excessive wear of brake system parts, linings, pawls, and ratchets.
- Load, wind and other indicators over their full range, for any significant inaccuracies.
- Gasoline, diesel, electric or other power plants for improper performing or noncompliance with applicable safety requirements.
- Excessive wear of chain drive sprockets and excessive chain stretch.
- Electrical apparatus for signs of pitting or any deterioration of controller containers, limit switches and push-button stations.

NOTE: Maintain inspection reports in a permanent file for five years. Include any outside maintenance service records in this file.

Crane/Hoist Hooks

A yearly MAG-particle tests is required of crane or hoist hooks. (A radiographic inspection may be substituted for MPI)

These annual inspections may be made by an outside inspection service.

Tests should be made of the lifting hook plus any hooks that support a block or motor drive, etc. Also, any critical stress point on cranes/hoists used for heavy lifts or applying unusual torque should be tested.

The inspection/testing records should be maintained with the monthly crane/hoists inspection reports noted in this section.

If hooks develop cracks, or are bent, or deformed, they should be replaced at once. Any new hook installed should be recorded in the permanent files.

Hooks should be removed from service if they are cracked, have been opened more than 15 percent of the normal throat opening measured at the narrowest point or twisted more than 10 degrees from the plane of the unbent hook.

Electrical Safety

- Only authorized employees shall perform maintenance or repairs on electrical wiring or equipment.

- The electrical "Lock Out/Tag Out" procedure shall be followed. No maintenance or repair shall be attempted until the lock out/tag out is in place to prevent start-up, movement or electrical shock. See the company Lock Out/Tag Out Procedure for more detailed information.

- No one will remove lock out tags, locks or multiple locking bars other than those who attached them. Locks shall not be cut off any lock out.

- All temporary electrical wiring shall be installed and maintained by qualified personnel in accordance with applicable codes.

- All electrical tools and equipment must be grounded or double insulated.

- Electrical tools or equipment shall not be used unless they have been inspected. Damaged or defective electrical tools must be properly tagged and returned immediately to the tool room for repair.

- Temporary electric cords must be covered or elevated. They must be kept clear of walkways and other locations where they may be exposed to damage or create tripping hazards.

- Equipment and vehicles shall not be driven over any power cable, unless the cable has been physically protected from damage.

- Booms and masts of equipment shall not be operated within 12 feet of an energized overhead high voltage line.

- All outlets, switch boxes, and breaker panels will be covered to prevent accidental contact of personnel with energized circuits or wiring.

- High voltage areas and equipment will be posted. All electrical panels and switch rooms will be kept clear to allow access to the disconnects and breakers in an emergency.

- NEVER use any electrical cord that has cut or cracked insulation.

Hand and Power Tools

- Power Saws, Grinders, and other power tools must have proper guards in place at all times.

- Power tools shall be hoisted or lowered by hand line, never by the cord or hose.

- Hand held power tools shall not be operated unless they are equipped with controls requiring constant hand or finger pressure or are equipped with friction devices.

- Cords or hoses must be kept out of walkways and off stairs and ladders. They must be placed so as not to create a tripping hazard for employees or be subjected to damage from equipment or materials.
- Hand tools shall be used for their intended purpose only. The design capacity of hand tools shall not be exceeded by using unauthorized attachments.

- Only assigned employees who have been instructed and trained in their safe use may use power activated tools.

- The use of power tools is prohibited in explosive or flammable atmospheres.

- Employees shall maintain all hand tools in good condition.

- Do Not use defective tools. If found, tag the tool and report them to your supervisor. Defective tools should be returned to the tool room for repairs.

- Grinders (pedestal or bench type) must be inspected monthly and the reports filed.

- Bench grinder tool rests shall be maintained not to exceed 1/8-inch distance from the grinding wheel or brush.

- Gloves shall not be worn while operating drill presses or bench grinders.

- Air Pressure on Pneumatic tools shall be valved off and bled down before the tools are disconnected from the air supply.

- Air Hoses shall not be crimped and/or tied off.

- Do Not use any electrical tool while standing in water.

Fire Prevention and Protection

Fire

- Know the alarm signal.

- Know how to turn in an alarm.

- Know the location of fire fighting equipment and how to use it.

- Fire extinguisher's must be readily available throughout the offices and shops, and must be on hand for welding, burning or electrical fire hazards.

- If an extinguisher is used, contact your supervisor to have the extinguisher recharged.

- Fire fighting equipment shall be inspected regularly and the results recorded and filed.

- Know the number for the local fire department.

Classes of Fires

Use the appropriate fire-fighting equipment:

- Class A Fires - Wood, Paper, Trash, etc.

  Use pressurized water, foam, CO_2, or Dry Chemical

- Class B Fires - Oil, Grease, Gasoline

  Use Foam, CO_2, light water & PPK, or Dry Chemicals

- Class C Fires - Electrical

  CO_2, Dry Chemicals - "NO WATER"

Actions on Outbreak of Fire

- If you can Easily extinguish it, DO SO.
- If the people nearby can control it, notify the nearest supervisor. The supervisor will determine whether to sound the alarm. Meanwhile, those nearby should attempt to control it.
- If it is obvious that it cannot be controlled, SOUND THE ALARM IMMEDIATELY, then notify the nearest supervisor.
- If in doubt, Sound the Alarm.

Safety

- Smoking is prohibited while using, dispensing, or in the vicinity of flammable or combustible liquids, or as otherwise posted.
- Flammable and combustible liquids shall be used and stored away from ignition sources.
- Flammable and combustible liquids shall be dispensed from approved safety cans and stored in approved safety cabinets.
- Gasoline powered equipment shall not be filled while the engine is running.
- Unobstructed access to fire extinguishers and other fire fighting equipment shall be maintained.
- Only approved solvents shall be used to clean parts and equipment. Solvents shall not be left in open containers when not is use. They shall be stored in approved, closed containers.
- Oily rags, trash, and other combustible scrap materials shall be placed in their proper receptacles.

- Machinery shall be kept free of accumulations of dirt and grease.

"Good Housekeeping and Common Sense Can Prevent Most Fires from Getting Started."

Welding and Burning

- Do Not use welding or cutting equipment unless properly instructed.
- Keep flame, slag, sparks and hot metal away from combustible materials, especially flammable liquids. Have a fire extinguisher within easy reach.
- Assure proper ventilation when welding, cutting or burning in confined spaces or with exotic metals.
- Employees shall wear appropriate welding protective apparel, including proper density lens protection.
- Check with your supervisor before any welding, cutting, or burning is done.
- Do Not use matches or lighters to light torches. Spark igniters must be used. Torches are not to be used to light smoking materials.
- Cutting, welding or burning shall not be conducted on tanks or drums that have contained flammable liquids or grease until they have been thoroughly cleaned or other precautions taken to prevent fire or explosion.
- When a special wrench is required to operate the acetylene cylinder valve, the wrench must be kept in position on the valve.
- Oil and grease shall be kept away from oxygen and acetylene gauges and valves.
- Always consider compressed gas cylinders as full and handle them accordingly.
- Never drop cylinders or permit them to strike each other.
- When cylinders are empty, turn them off, remove gauges, put on a protective cap and store them in the proper holding area.
- When transporting, moving, and storing compressed gas cylinders, the protective caps shall be in place.

- Do Not use a wrench on a valve equipped with a hand wheel.

- Compressed gas cylinders must be secured in racks or with safety chains at all times. NEVER leave a high-pressure cylinder standing alone.

- Do Not store oxygen and acetylene cylinders together.

- Mark empty cylinders when used and store them in an area separate from full cylinders.

- Do Not use compressed air or oxygen to dust off hands, face, or clothes.

Hazardous Areas and Materials

Hazardous Entry

Employees shall not enter closed or confined tanks, bins, or vessels that have contained hazardous materials, atmospheric contamination or conditions that could be injurious before an air quality check has been conducted. For detailed information, see the company's Permit Required Confined Space Program.

Employees required to enter contaminated tanks, bins, or vessels shall wear the appropriate respiratory protection, including self-contained breathing apparatus, as directed by management.

Employees performing hazardous entry work will wear safety belts and lifelines as approved by the safety group. A line tender will be equipped with the same equipment as the person performing the work, and be prepared to assist if necessary.

Radiation (X-ray)

Radiography is normally performed by third parties not directly under company control. Radiographers are required to submit copies of procedures and safety guidelines before commencing work.

- Supervisors will check for proper certification of technicians involved.

- Supervisors will insure that technicians post warning sings and establish barricades before beginning operations.

- Radiographers and their assistants shall use survey instruments, film badges and dosimeters as required by applicable regulations.

- All employees not issued dosimeters will stay clear of the designated hazardous area.

- It is the radiographer's responsibility to keep all personnel out of hazardous areas and keep hazardous materials away from personnel.

Explosives

- Only authorized employees shall store, transport, handle or use any explosive materials.
- All explosives shall be stored, transported and used in accordance with applicable regulations.
- Blasting will be performed at scheduled blasting times and shall not commence until it has been made certain that no one is in the blasting area.
- Unattended explosives, explosive material and open magazine storage shall be immediately reported to your supervisor.
- Smoking, matches, open flames or other spark producing devices are prohibited in or within 50 feet of explosives magazines or while explosives are being handled, transported or used.
- Explosives must be stored in approved magazines; unused explosives must be returned to the magazine immediately.
- Detonators shall not be stored in the same magazine as other explosives.
- Magazines and box-type magazines shall be suitably labeled, posted and locked.

Hazardous Materials

- All personnel must be trained in the Hazmat Right to Know requirements and the Hazmat labelling procedures.
- Only approved containers shall be used for the storage and handling of flammable liquids and other hazardous materials. All containers must be properly labelled.
- Oily rags will be disposed of in metal containers with lids.
- Paint and other hazardous materials will be stored in approved lockers or sheds after opening.
- Machinery shall be kept free of accumulations of dirt, fuel, grease, and oil.

- Gasoline shall not be used for cleaning purposes at any time.

- Flammable solvents and cleaning liquids will only be used in well-ventilated areas away from any source of ignition.

- Employees using or handling hazardous materials will wear proper personnel protective equipment. Know the First Aid procedures for the substance being handled.

- Material Safety Data Sheets are available for any hazardous materials used in the shop. If in doubt as to the safety precautions to be taken, or how to dispose of any materials, contact your supervisor, or the Regional Safety Office.

- <u>DO NOT USE ANY MATERIALS BEFORE VERIFYING THE PROPER SAFETY PRECAUTIONS THAT MUST BE OBSERVED.</u>

Material Handling and Storage

Severe injury can result from improper lifting techniques. Lifting can be easy and safe, if it is done the right way.

Follow these steps whenever you lift a heavy object:

- If the load is too heavy, get help.

- Wear gloves to protect hands.

- Be sure to have a good footing.

- Feet parted, one alongside, one behind the object.

- Bend your knee and crouch down to the load.

- Keep your body close to the load.

- Get a good grip with the whole hand.

- Keep your back straight, nearly vertical, and lift with your legs.

- Avoid twisting your body. Shift your feet instead.

- Be sure you can see where you're going.

- To lower the load, reverse the above procedure.

In addition, the following procedures will be followed:

- Heavy or awkward materials shall be moved with mechanical aid or with additional help to prevent a lifting hazard.

- Materials and supplies shall be neatly and securely stacked, blocked and limited in height so as to be stable and in no danger of collapsing, sliding, or falling over.

- Heavy items shall be stored on lower shelves and blocked against falling or rolling.

- Materials shall not be permitted to protrude from shelves in such a manner as to create a hazard.

- Storage of acids or caustics shall be maintained on the lowest available shelf or rack, or stored in an approved cabinet.

- Dangerous or hazardous materials must be labeled as to contents and precautions during use. Check the Material Safety Data Sheet before using. Insure the proper Hazmat shipping documents accompany the shipment.

Sandblasting and Painting

- Only trained personnel should be permitted to perform sandblasting and/or spray painting.

- No other employees may enter the sandblasting/spray painting area when either of these operations are in progress.

- There will be No Smoking or open flames during painting operations.

- Operators will wear approved personal protective equipment.

    - Sandblasting--Operator and pot tender, air supplied hoods, with gloves and protective clothes. If the air supply hood is not rated to provide hearing protection, then approved hearing protection must be worn under the hood. Approved respirators must be worn if the air supply hood is not rated to filter out silica dust.

    - Spray painting--Only approved cartridge type spray paint respirators may be worn during this operation. Eye protection, such as cover goggles, may be needed to keep spray out of the eyes. Protective clothing and gloves are recommended.

- Check all hoses, connections, and valves before use.

- Only an approved and checked air supply may be used for the air supply hoods.

- Where work requires respiratory protection, employees shall limit the growth of facial hair in the seal area of the respirator to insure the effectiveness of the respirator.

- Respirators are to be checked out to individuals and inspected before and after each use as well as kept clean. Check out forms and cartridge inspection forms must be maintained.

Ladders, Handrails and Machine Guards

- All ladders shall be in good condition. Broken or damaged ladders must not be used. Repair or destroy them immediately. Ladders to be repaired must be tagged "Do Not Use."

- No more than one person at a time on a ladder.

- Wooden ladders should not be painted.

- The base of the ladder must be set back a safe distance from the vertical, approximately one-forth of the length of the ladder. Secure the top of the ladder to prevent movement.

- Whenever ascending or descending a ladder, employees shall face the ladder and use both hands and feet.

- Before using any ladder, be sure that the soles of your shoes are free of slick substances.

- Ladders used for diving operations are to be constructed so they reach below the water surface by more than three feet.

- Only approved scaffolds shall be used. Barrels, boxes and other makeshift substitutes for scaffolds shall not be used.

- Scaffolds shall be substantially constructed to carry the loads imposed upon them and to provide a safe work platform.

- Do not overload scaffolds. Materials shall be brought up as needed. Scaffolds must not be loaded in excess of one-fourth of their rated capability.

- Scaffold planks must be visually inspected before each use. Damaged scaffold planks must be destroyed immediately.

- A handrail must be provided on at least one side whenever a ramp or stair presents a hazard to employees.

- Gears, sprockets, chains, drives, couplings, flywheels, shafts, saw blades, fan blades and similar exposed moving machine parts, which may be contacted by persons and which may cause injury, shall be adequately guarded.

- Employees shall immediately report any guard that is missing or damaged.

- Guards shall be kept in place on tools and equipment. Machine guards and safety appliances shall not be removed or made inoperative, except for the purpose of making repairs.

- All portable ladders shall be inspected monthly. Inspection reports will be maintained in a file.

Miscellaneous Safety Rules

- Floor openings, raised platforms, or holes shall be protected by an approved guardrail or covers.

- Repairs involving high-pressure systems, such as air lines, receivers or compressed air equipment shall not be attempted until the pressure has been relieved.

- Wire, metal, or plastic light-bulb guards must always be in place on all droplights except when replacing burned-out bulbs.

- Gasoline can be highly explosive. "No Smoking and No Open Flames". Signs must be posted wherever gasoline is stored or handled. Take care to avoid overfilling gasoline tanks. If gasoline is spilled, clean it up immediately and wash down the area.

- Do not remove warning signs or posters from any equipment.

- All personnel will use appropriate Fall Protection when working more than 6-8 feet above a work surface, unless handrails are provided.

Accident Reporting

All accidents and near-miss incidents shall be reported without exception.

SAFETY PROCEDURES DURING MAINTENANCE

Hydraulic Systems

Whenever servicing work is carried out on a hydraulic system, the overriding consideration shall be one of safety of the technician, his colleagues and the personnel around him. Although safe working practices rely largely on common sense, it is very easy to overlook a potential hazard in the stress of a breakdown situation.

Maintenance personnel shall therefore discipline themselves to go through a set procedure before commencing any work on a hydraulic system. As hydraulic fluid is only slightly compressible when compared to gasses, only a relatively small amount of expansion has to take place to release the static pressure. When compressed gas is present in a hydraulic system, either through ineffective bleeding or where an accumulator is fitted, extra care must be taken to release the pressure gradually.

Safety Steps

Safety steps to be taken before working on any hydraulic equipment are as follows:

- Lower or mechanically lock, any suspended load.
- Shut down system.
- Exhaust any pressure that may be locked in the system.
- Drain down all accumulators/cylinders.
- Discharge both ends of intensifiers.
- Isolate the electrical control supply.
- Isolate the electrical power supply.
- Recognize valve types before removing "cartridges" as some may have locked in pressure.

Electrical Safety

Main Power into System

Main 440V Supply

The system Supervisor shall request of the Rig/Vessel Electrician that the power be switched OFF. The appropriate permit to work from the Client shall be duly signed by both parties and the supply shall be locked in a suitable fashion with the correct warning sign displayed.

On completion of task the Supervisor shall request of the Rig/Vessel Electrician that power be switched back on. The "Lock Off" device and Warning Notice shall be removed and the permit to work signed off.

Motor/Alternator Supply

ROV System Circuits

If work is to be carried out on the power circuits of the ROV System, the motor/generator unit shall be switched off and breaker shall be locked off and a Warning Notice displayed.

Work on the Motor/Alternator

If work is to be carried out on the motor Alternator itself, it shall be in accordance with the paragraph above.

Diesel Generator Supply

When a Diesel Generator is the power source, the breaker from the electrical supply shall be locked off and a Warning Notice displayed. The generator shall also be switched off during this time.

Electrical Domestics in Control Container

Systems with a domestic consumer unit

If a "Domestic Consumer Unit" is installed the appropriate fuse shall be withdrawn to allow work to be carried out.

Systems without a domestic consumer unit

If no Consumer Unit is installed, the ring main shall be isolated at the appropriate point and Warning Notice displayed.

Power Distribution Unit (PDU)

Before any work is carried out, the main breaker shall be in the OFF position, the main power fuses removed and a warning notice displayed. Any testing within the PDU shall only be carried out by a Competent Person specified by the Company.

If work is to be carried out on any of the circuits fed from the PDU, the appropriate breaker shall be in the Off position, fuses removed and a warning notice displayed.

ROV

The majority of work within the ROV requires AC Power to allow fault finding. This work shall only be carried out by a competent person specified by the Company.

At no time shall the main power connectors be left open on the ROV and unattended. If a plug is to be removed, the appropriate breaker shall be in the OFF position and the fuses removed.

General

- At all times the transformer cover plates shall be in place, clean, and retained by the correct number of fasteners.

- All works carried out shall be completed and signed off by a competent person.

- Trainee Technician work shall be supervised by a Senior Technician and finally checked by him.

- A high standard of work is to be maintained at all times and code of practice implemented.

- Long lengths of umbilical and transformers act as efficient storage mediums and the stored electrical charged can cause damage or injury, even when there is not power applied to the system. Always discharge them before working on them.

- Ground straps to be attached to the ROV at all times while on deck.

- When working with High Voltage circuits the appropriate safety equipment and materials will be used.

SAFETY CONSIDERATIOINS AND REGULATIONS

The International Marine Contractors Association (IMCA) represents offshore, marine and underwater engineering companies and is a good source of reference information regarding the safety and operation of equipment offshore. Their goal is to promote improvements in quality, health, safety, environmental and technical standards through the publication of information notes, codes of practice and by other means. They are organized into four distinct divisions, each governing a specific area: Diving, Marine, Offshore Survey, Remote Controlled Systems and ROVs. The Remote Controlled Systems and ROV Division is concerned with all aspects of the equipment, operations and personnel involved with the remote controlled systems (including ROVs) used in the support of offshore marine activities. They have recently released the "*Code of Practice for the Safe and Efficient Operation of Remotely Operated Vehicles*," which is available from the IMCA, Carlyle House, 235 Vauxhall Bridge Road, London SW1V 1EJ, UK.

Additional information is provided in the references listed in the bibliography of that publication, which are listed below for those who need more definitive guidance in the specific areas addressed. These references are also available from the IMCA address above.

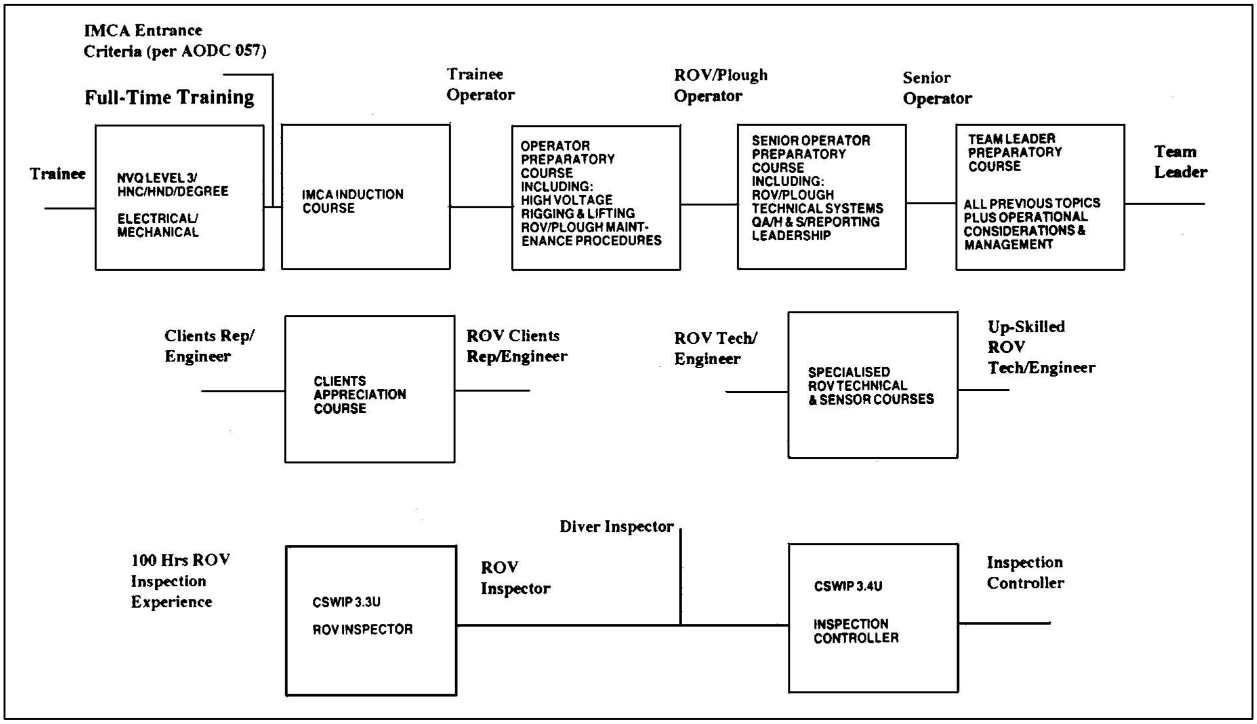
PUBLICATION NUMBER	TITLE
AODC 036, Rev 1, April 1994	The Initial and Periodic Examination, Testing and Certification of ROV Handling Systems
IMCA R 003, May 1997	Guidance on Termination of Load Bearing Umbilicals or Lift Cables used in ROV Handling Systems
AODC 032, Rev 1, September 1992	ROV Intervention During Diving Operations
IMCA, 103 DPVOA, January 1995	Guidelines for the Design and Operation of Dynamically Positioned Vessels
IMCA R 001, October 1995	Plastic Spherical Air-Filled Fishing Buoys
AODC 035, September 1985	Code of Practice for the Safe Use of Electricity Under Water
IMCA R 002, July 1996	Basic Level of Competence to be met by ROV Personnel
AODC 060, August 1993	Safety Procedures for Working on High Voltage Equipment

TRAINING

The cost of operations using ROVs can add up when considering ship costs, etc., thus, there is a growing desire to ensure that operators are proficient at their job when they arrive at the work site. Other than on-the-job training, there are three methods to achieve this–physical training centers that offer hands-on experience with actual ROVs, similar courses provided in-house by major operators or manufacturers, and the latest technology, which uses virtual environments that could be a part of either of the previous two. All will be discussed in the following sections, along with some of the existing politics that revolve around training. In addition, a listing of organizations that provide ROV and/or related training is provided in Appendix E.

Requirements

In recent years there was a push to require a training certificate for ROV operators, however, the International Marine Contractors Association (IMCA) Remote Systems Division decided they would not proceed with the "Certificate of Competence." In an article in Underwater Systems Design, author Chris Bell of SubServ points out some excellent aspects of training that is necessary, even if not officially required, for ROV operators. The following figure outlines the training program.



Typical ROV training course structure
(Source: *Underwater Systems Design* magazine)

The author further breaks down the training requirements into the following areas:

- Full-time training and modern apprenticeships

  Would apply where company's plan to use young apprenticeship personnel or government assistance is available.

- Introduction courses

  Typically, 5-day courses that are performed in-house or at training centers that are modeled after AODC 057 requirements.

- Cross Training

  Electrical and mechanical personnel should be cross-trained in the basics of each other's discipline.

- Maintenance Courses

  ROVs are becoming more reliable than ever, however, down time can be very costly, as discussed elsewhere in this publication. Maintenance proficiency is necessary for not only the ROVs and related systems, but also many of the subsystems, which may require specialized personnel within ready access for repair or replacement tasks.

- Health and Safety Courses

  Basics in offshore operations such as "rigging and lifting" and "high voltage equipment" are essential. Today, the Health and Safety at Work Act also applies to offshore operations.

- Teamwork and Leadership Courses

  Offshore is a stressful environment and such courses are essential to prevent problems between personnel.

- Inspection Courses

  Courses such as CSWIP 3.3u ROV Inspection and CSWIP 3.4u Inspection Controller should be taught.

Although one could over train personnel–training does not come cheaply in time or money–statistics show that properly trained personnel provide the following benefits:

- Increases corporate professionalism
- Reduces down-time
- Increases personnel retention
- Reduces liability

Today, the industry faces a high-cost environment; an environment where trained operators are in high demand and are subject to being pulled away by competitors. With the bottom line always in mind, the wise operator will strive to have not only a well-trained crew, but a satisfied one. Some of these points will be addressed in the following section.

Training – The Bottom Line

There is tremendous pressure on personnel throughout the offshore industry. Personnel training and safety are fundamental issues that require far more than lip service. Presently, there is a critical shortage of trained, competent, experienced personnel. As offshore expansion increases, the challenge to personnel safety also increases. With this expansion there is an influx of inexperienced personnel, which requires an increased commitment to safety. Offshore teams and being diluted. An investment in professional training is an investment in safety.

Oceaneering has taken the above considerations seriously. Their training plan is discussed in the following paragraphs. Oceaneering uses full time professional recruiters whose responsibilities are to identify and hire the trainees required to support the company's planned growth. They established an in-house training school in 1995 and provide it with a $1 million/year budget. Each recruit receives approximately $20K in training before he ever goes offshore. Oceaneering plans to add 100 operators per year from 1997 through 2000.

Although hiring from one's competition may solve the immediate problem, the practice of "personnel piracy" becomes a Zero Sum Game. Not only does it increase costs, it dilutes and/or damages all of the philosophical and cultural standards: culture, commitment, safety, accountability. Teamwork becomes small talk and chemistry, trust, cross-training, and interdependence among people is damaged by such a short-term approach. It reflects a lack of belief in, and commitment to, the future. The bottom line is that hiring from the competition does not address industry's shortages, it just adds to the escalating costs and declines capabilities.

So, if training is omnipotent, who is Oceaneering training? Basically everyone:

- Recruits
- Retraining/upgrading experienced personnel
- Supervisors to be Team Leaders
- Superintendents to be Project Managers
- Cross-training in all disciplines

Oceaneering's primary training facility in Morgan City has two full time instructors, three specialized instructors, classrooms, electronics and hydraulics labs, test tank, ROV system and an ROV trainer/simulator. They also provide training in Aberdeen, Stavanger, and Singapore.

Oceaneering feels that hands-on training is fundamental – something that is essentially prevented by the practice of two man ROV crews offshore. The apparent cost saving by reducing the team essentially eliminates a good slot for a junior person to learn the trade. In the shallow waters–656 to 984 ft (200 to 300 m)–of the Neutral Basin of the North Sea, the two man team has resulted in a false sense of security, a sense that can end up in heavy periods of down time if the mind-set continues into the deeper, harsher environments offshore. Teams should be expanded to allow adequate development of skills and capabilities–both require practice.

ROV Trainer and Simulator

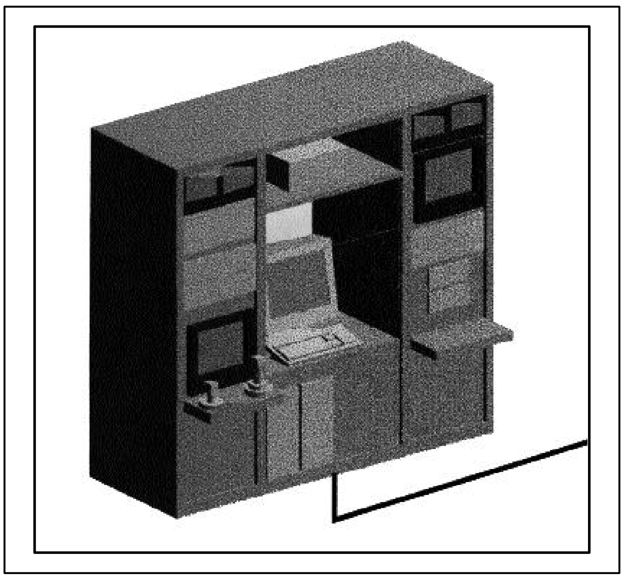
The future will see an increase in ROV simulators, such as those discussed in the next section. Oceaneering's training plans also include such a high fidelity, full-scale system. Their ROV trainer and simulator is intended to develop both piloting and navigating skills in inexperienced pilots and to evaluate these skills and the individual improvements against an expanding database. It will also allow subsea work tasks to be set up and various configurations of conditions to be evaluated for effectiveness, performance, etc. This will allow new/difficult subsea tasks to be simplified and/or modified as the results dictate. It also allows for the training of personnel on difficult, low cost tasks before going offshore. Oceaneering believes that this capability will become increasingly valuable as the range of ROV tasks are expanded. The simulator will be able to program the following:

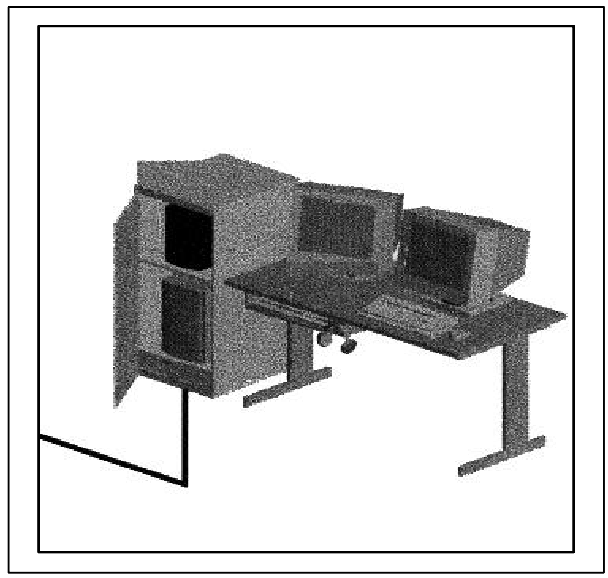
- Environmental Variables
- System Variables
- Sub System Failures
- Job Types and Tasks

Simulation of vehicle dynamics will feature a high fidelity, six degree-of-freedom hydrodynamics model that realistically simulates vehicle handling characteristics in a variety of ocean current conditions. It will also have an ocean bottom collision detection algorithm.

The ROV Trainer & Simulator will be a full scale *Magnum/Millennium* console. Since a primary ability to operate an ROV is simply knowing where information appears, what it represents, and how often the pilot needs to reference it–the fidelity of the console is fundamental. Accordingly, the trainer will activate all gauges, displays and sensors.

The environmental simulation will feature any piece of subsea equipment that is necessary. These can be imported from industry standard CAD files or oil/gas exploration and production objects as required. The environment will feature a 5x5 nautical mile (9x9 km) operational area with selectable ocean bottom terrain. Necessary objects can be positioned anywhere in the environment and the following ocean current parameters can be varied: speed, direction, and turbulence. Oceaneering's ROV Trainer & Simulator is shown in the following figure.





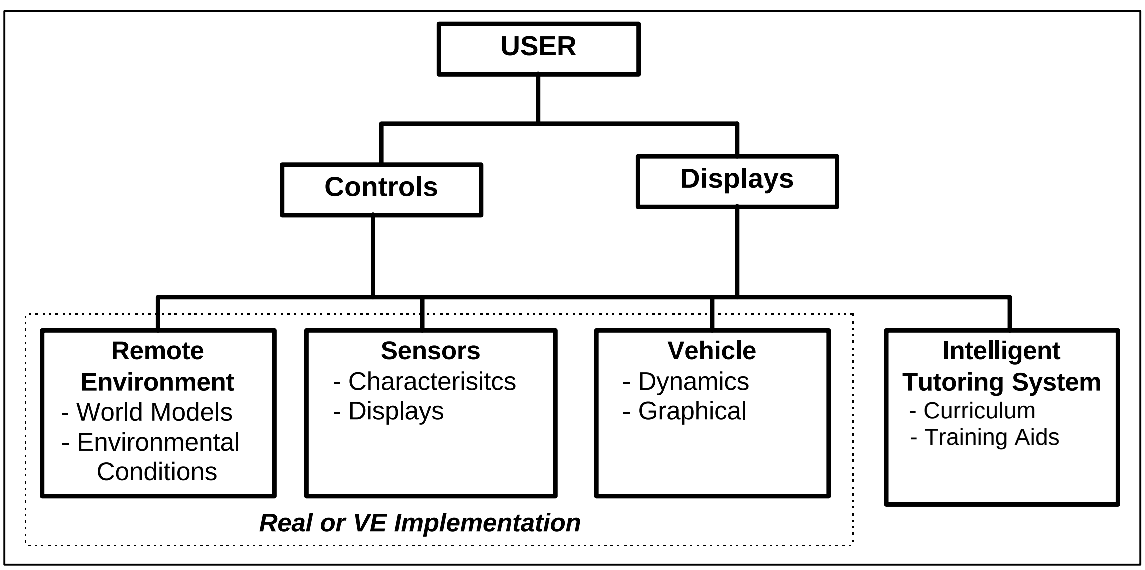
Oceaneering's ROV Trainer & Simulator

The following section will discuss the next level of technology for training ROV operators: a virtual environment that can simulate any ROV or task.

Training in the Virtual Environment

Although hands on training using actual ROV systems will not be totally replaced, the idea of using a computer based virtual environment (VE) does have its positive aspects. One of the most significant benefits of a VE is that the training can be conducted at the work site, without launching an ROV or requiring the operator to travel to a facility designed for operator training. Thus, the trainee is on station earning his keep, and the company's, which has a positive effect on the logistics and cash flow. Other benefits of a VE based system is the creation of a flexible environment that permits the simulation of a wide range of vehicle types, operational environments, mission scenarios and operating aids. This will allow better mission planning and rehearsal, thus honing operator skills, which will ultimately enhance operator performance during actual ROV operations.

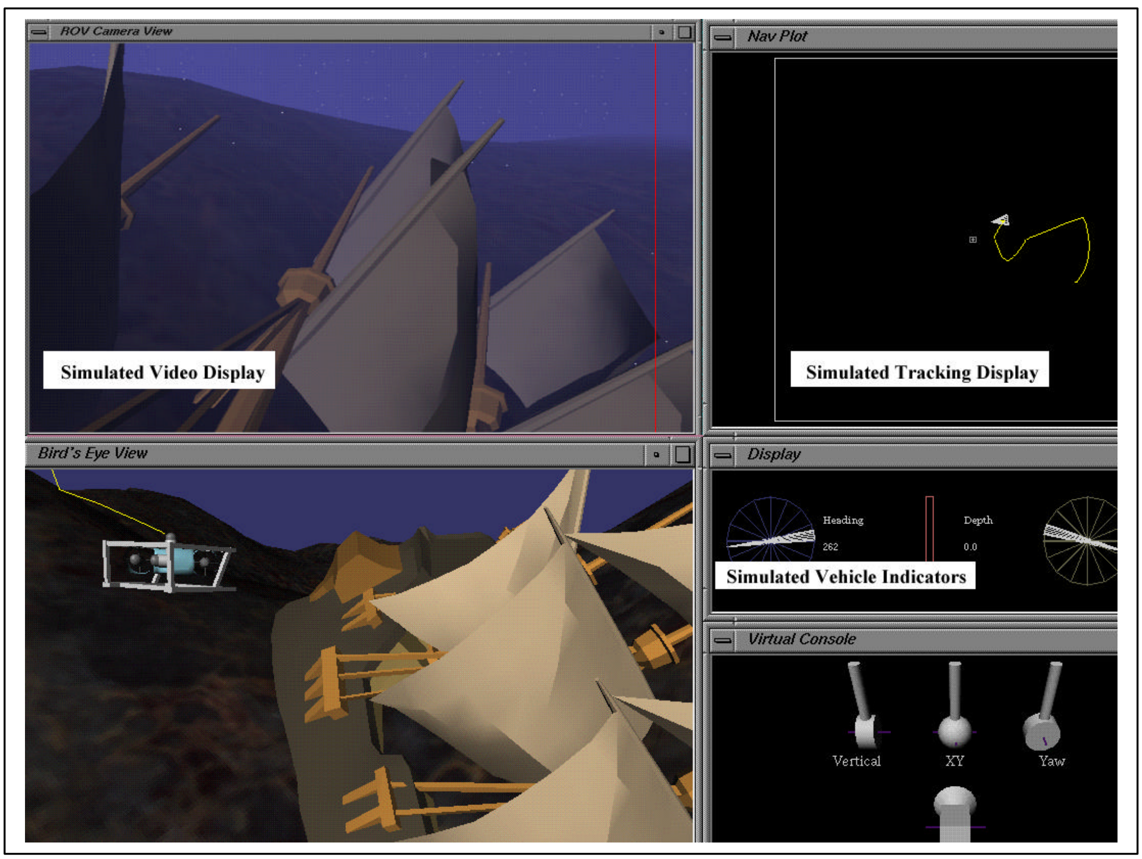
One company working in this area is Imetrix, Inc., of Cataumet, MA, which is being funded by the US Office of Naval Research. The program is called Training for Remote Sensing and Manipulation (TRANSoM). The primary system components are shown in the following figure. The project intends to create a VE where ROVs can be operated, performing tasks from simple training to complex mission scenarios. Existing models and data files such as AutoCAD models can be used to build realistic representations of actual operating areas and equipment. With offshore work sites being designed ahead of time to allow remote intervention, this could become a very powerful tool, not just in training, but in optimizing the design of the actual hardware being installed underwater.



Primary system components

Environmental variables that affect ROV mission performance can also be modeled in the VE. Some of the factors included in the training system are current (velocity and direction), water visibility, and the number and size of obstacles. During training exercises, these factors may be varied independently or in combination to create progressively more challenging scenarios to provide an opportunity for development of piloting skills. Both the dynamics of the vehicle and the tether are incorporated to closely approximate the actual behavior of the system.

The sensors available to the operator also play a major role. The video simulates many characteristics found in actual systems including tilt, zoom, lighting, and the effects of poor water visibility. The tracking display provides an XY plot of the vehicle position and heading, which may be augmented with additional information for instructional purposes. Required displays can be simulated as shown in the following figure. Sonar models can also be included. Such a training system will allow future investigations of sensor displays such as: head mounted, see-through head mounted, and wide screen.



Training display showing VE world and displays

__The Tutoring System__

There are three main components to the design of the VE training system: developing the curriculum, determining how it will be taught, and developing the tools to aid in the teaching process. The training element is a form of computer aided training known as an Intelligent Tutoring System (ITS). This system uses a variety of training aids and interventions to coach the student and guide his progress as follows:

__Curriculum__

A series of curriculums guide the operator through a defined series of skills until he is deemed proficient. The level of difficulty can be adjusted based on the student's competence. The four basic skill areas are:

<u>Maneuvering</u> is the ability to drive the vehicle to a desired location and orientation. In order to maneuver the vehicle effectively, the operator must incorporate an understanding of the vehicle configuration, momentum, drag, effects of the controls, as well as basic hand-eye coordination.

<u>Sensor Integration</u> is the ability to interpret the available sensor information and to piece together the whole picture. While many different sensors are used in conjunction with ROV missions, instruction and practice is required in to effectively use the available information. Sensor related skills range from the intuitive use of video to the more cognitive skills of interpreting sonar and navigation data.

<u>Situational Awareness</u> is the overall knowledge of vehicle status, including the location of the vehicle and tether within the environment, and the status of mission progression. With a tethered system, understanding and having a mental model of where the vehicle has been, where it is and where it is going, is the most vital skill for successful operation.

<u>Mission Operations</u> skills include the knowledge of the variety of systems often used in conjunction with ROV operations. Key to the success of any mission are the abilities to plan trajectories, manage multiple tasks, communicate with other operators, and develop effective team coordination.

__Training Scenarios__

The overall training system is based on a coached apprenticeship model, where the trainee has both the opportunity to watch and to practice the skills being taught. A typical training session proceeds as follows:

<u>Introduction</u> is where the task is named and explained, using visual aids and sample displays as necessary. For example: "Transit from point A to point B."

Demonstrations are pre-programmed task segments, using the simulation capabilities of the VE. Pertinent skills and performance parameters are highlighted by the Tutor, alerting the trainee to the focus of the exercise.

Practice allows the student to perform the task, with interventions by the Tutor as required. As the student gains proficiency, these aids are faded out, permitting the student to operate independently. For example, the 3D view is an artificial aid to operation that is faded out as the trainee becomes proficient in using the standard ROV displays.

Playback and Critique allows all or part of the session to be replayed, with accompanying notation as to errors made. During the playback, the student may re-enter the simulation in an effort to correct individual mistakes at the time they were made.

Repetition of the Practice and Playback steps are performed until the student demonstrates the desired level of performance. At that time, the task may be modified to make it more difficult or additional tasks included.

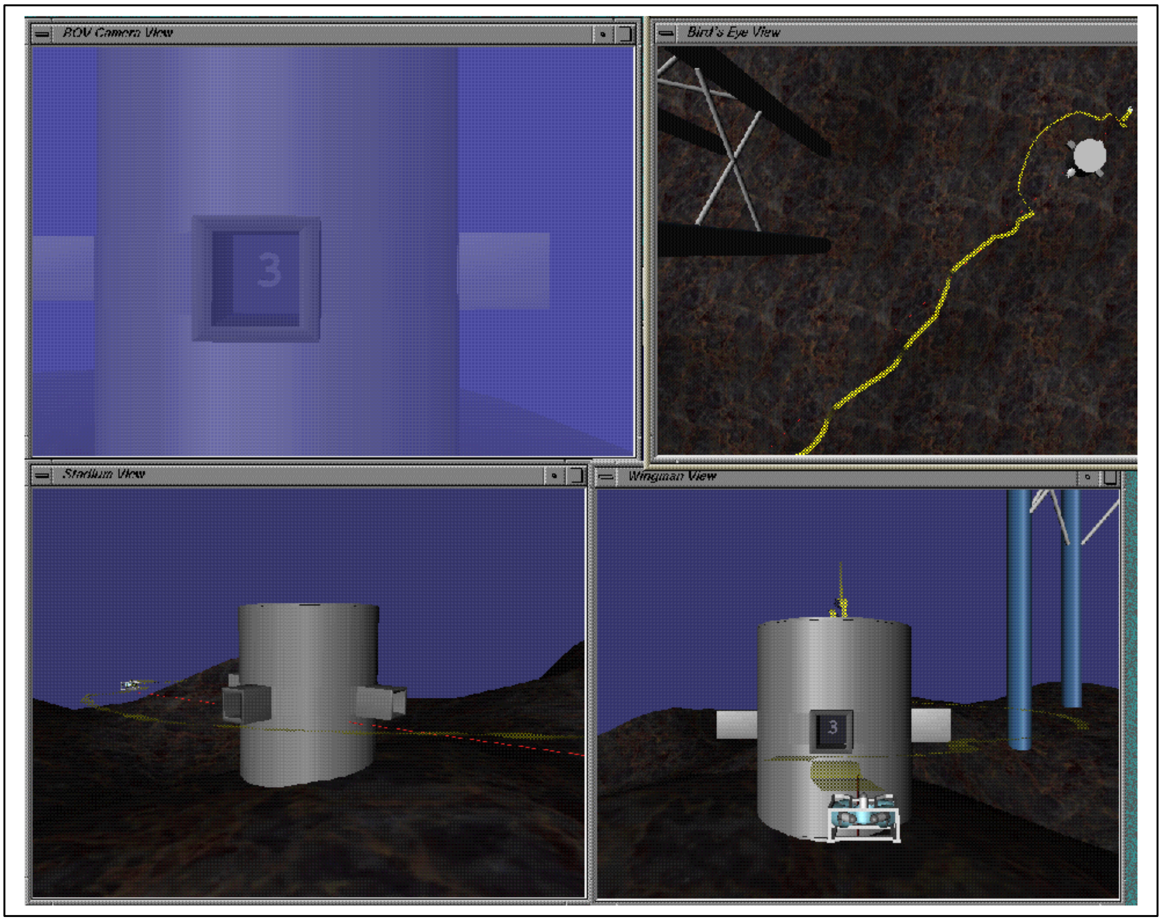
Aids and Interventions

Chosen from traditional classroom techniques, computer aided training, and VE-unique capabilities, a variety of training aids and interventions are incorporated in the training system. These include the following:

Demonstrations are programmed mission segments, which illustrate particular skills to be learned. The system offers a variety of ways to demonstrate to the trainee the desired behavior. For example, the ROV model may be automatically flown along a planned path while the proper control inputs are indicated.

Coaching is a key feature of the ITS. Provided verbally and in stages appropriate to the error, coaching permits the trainee to receive instruction without distraction from the visual displays. The trainee also has the ability to query the system for additional explanation, if needed.

VE Views offer a unique ability to provide the operator with a variety of viewpoints augmenting that of the simulated ROV camera view. The following figure compares some varying viewpoints including the camera, bird's-eye view, an oblique "stadium" view, and an over-the-shoulder wing-man view. These are provided upon request to provide the trainee with an overall sense of the vehicle's location and situation. They are then removed to reduce dependence on them. The addition of these viewpoints is also being evaluated as a performance aid to existing ROV piloting stations.



Available VE Views: Camera, Bird's Eye, Stadium, and Wingman

Visualization Aids are additional visual cues that are provided to draw attention to particular items and to provide instructional information to the operator. These include marking of the actual and desired path, particulates flowing by to indicate direction of motion, a laser "pointer" to indicate direction of camera view, and a floating compass rose by the vehicle to indicate the vehicle heading at all times.

Replay of a session or sequence permits the trainee to observe his actions while giving him a chance to correct errors made. Upon completion of the practice session, the trainee receives a list of those errors made. He may then replay each to see at what point they occurred. Hints are available to the trainee that provide possible methods of correcting the errors. He may then restart the simulation just prior to the error, and retry using the knowledge gained.

The flexibility of the VE modeling permits a wide range of environments and mission scenarios to be implemented. The realism of the simulation permits an operator to plan in advance his approach to the mission including such parameters as the placement of sensors and sequencing of tasks. Various environmental conditions can be implemented to observe their effects on mission operations, and to provide for contingency planning.

There will definitely be a place in the future training environment for VE based systems similar to that just described. Although “class room” training systems will not equal the effectiveness of on-site experience with an actual ROV, they will play an ever increasing role in providing an operator with a “license” to go offshore and enter the real world–just as simulators are used to aid military and commercial pilots. Proficiency comes from hands-on experience, however, the prudent ROV operator will follow this technology and use it to leverage his competitiveness in the future.

LEGAL CONSIDERATIONS

Insurance

General

ROV contractors, as with all oil and gas service companies, require standard insurances to cover employer's liability, workers compensation and property damage.

This varies greatly geographically and the requirement by clients also may vary dependent upon the individual client's policy, the scope of supply and the level of risk the ROV contractor is expected to absorb.

It is not the intention of this publication to elaborate on these insurances, but to focus on the requirement for loss or damage insurance on the ROV hardware itself.

Values

ROV system capital values range between $650,000 to over $3,000,000 with over 50 percent of the value of each system regularly submerged and, as such, exposed to loss or damage.

Though systems have become far more reliable over the years, instances of loss still occur and insurance claims still result. As such, insurance is expensive and becomes a key component of operational costs.

Most companies tender their insurance requirements annually through brokers who place insurances through large insurance companies primarily in Europe. Typically, equipment is insured under three categories:

1. Overside (equipment that is submerged)

2. Topside (equipment that remains on deck)

3. Onshore (applied when equipment is stored onshore)

Each category attracts different risk as a percentage of its capital value. For example, the equipment that is submerged regularly on one particular ROV system may have a replacement value of $850,000. One could estimate that this equipment may be utilized 80 percent of the year, being submerged for 60 percent of that time. If the insurance premium were five percent on the submerged equipment, then the annual cost would be $20,400. Topside components, because there is less risk, attract a lower premium.

Insurance companies usually insist on a minimum premium for each ROV system regardless of actual calculated use. Large deductibles are also common.

Precautions

As with insurance on housing or automobiles, there are ways to reduce the cost of insurance each year. The most obvious way, of course, is to reduce the number of claims made. Other ways include:

- Fitting of emergency location devices such as strobes that activate when the ROV surfaces
- Maintaining a slight positive buoyancy to ensure the ROV will surface
- RF beacons for tracking the system on the surface
- Acoustic beacons for tracking the system if submerged
- Sensible coloring to enable the ROV to be sighted from planes and helicopters
- Lost and found nameplates
- Implementation of emergency response procedures

Most professional ROV contractors adopt all of the above as standard.

Operational Considerations

One of the primary risks of damage or loss to an ROV system is during launch and recovery. The entrance and exit of the ROV and TMS through the transition zone (air/water interface) can place significant loading on the equipment and can put the system at risk of collision with the vessel or platform.

Companies usually have a standard policy as to what constitutes maximum launching criteria, which relates to wave height and wind force, normally adopting the Beaufort scale as the measure and typically "Force 6" as the barrier. However, this measurement can largely produce an irrelevant standard, as these conditions can increase or reduce the risk of deployment under different launching conditions. For example, a large DP vessel in rough weather can maneuver itself to provide a "lee-shore" during a launch and recovery. Some vessels also have a moonpool arrangement with a cursor system to protect the ROV during transition.

In some instances, wind and wave direction may not be uniform, and this can create either a very confused sea state or one that depresses wave height. Accordingly, it is best left to the ROV Supervisor, applying his experience and best onsite judgment, as to whether to launch or not. Some companies have standard waiver documentation that they request their clients to sign if the clients require them to deploy equipment against the better judgment of the ROV Supervisor. However, these documents are largely ineffective, as they are not binding, but they do assist as a deterrent to a risky launch of the system, which is the intended purpose.

Claims

Filing a claim for lost ROV equipment is no different than any other insurance claim. It is time consuming, tedious and a great distraction to management. Typically, operational reports must be filed by all personnel who witnessed the event, and management reports are required after personnel have been debriefed.

The insurance company may appoint a Loss Adjuster who will interview personnel and management, physically examine the remaining equipment (e.g., severed tether) and may visit the loss sight (vessel, drill rig, etc.). When all the relevant documentation has been filed, and all the relevant authorities are satisfied that the loss is legitimate, the claim can be processed. The lengthy proceedings can take in excess of six months before a settlement is reached.

Peculiar International Considerations

General

Offshore oil and gas reserves are located globally. Accordingly, international ROV services are required. With this comes the need to transport, deploy and operate equipment in some very diverse environments. Those companies that do operate internationally will experience many different forces that affect the undertaking of operations. These differences may be environmental, technical, logistical or cultural, but they do exist and are an important consideration.

Customs/Import/Export

The importation of ROV equipment into foreign countries can be simple and straightforward or complicated and very risky. Generally, most countries will allow the import of equipment for a specific project and/or client. And, providing the documentation is in order, there is no import duty applied, assuming the equipment is duly exported under the guidelines and within the time frame specified under the importation documentation.

Typically, a “proforma invoice” is prepared prior to shipment detailing a summarized inventory of the equipment, weights and dimensions and value in the currency specified. Some countries require this invoice to be in summary form only, while others expect an inventory accurate down to the last detail. This proforma invoice is then accompanied by a “bill of lading,” which is prepared by the freight forwarding company and the shipping line. On the receiving end, the equipment is subject to customs inspection and, again, this can vary from a tertiary inspection to a detailed inventory.

In many countries, certain goods are either dutiable or prohibited for import. This is usually due to policies implemented to protect local industries. For example, in Brazil and Indonesia many consumable goods cannot be imported and must be obtained locally. Importation of sophisticated, expensive and inventory intensive equipment such as ROV systems into third world countries can be a real challenge. Even well documented and planned shipments can become subject to “bonds,” “fees” and “fines” that neither you nor your agent was aware of.

The simplest way to import equipment is onboard the vessel, rig or barge that it will be operating from, then export it in the same manner. This normally allows the equipment to be imported as shipborne equipment, greatly reducing the risk and bureaucracy.

Taxation

Every country has its own peculiar tax regulations, which are a major consideration when working overseas. Many countries allow certain tax shelters based upon a maximum number of days worth of revenue earned within that country; others tax you on every cent of revenue derived within their territorial waters. In many cases, tax comes in the form of withholding tax as a percentage of revenue. This way, the relevant tax authority can be guaranteed revenue, and you are not required to file a return. Therefore, this means whether you are profitable or not, you will be taxed.

Where tax treaties do not exist, you may be taxed by the authorities in the area of operations, and by your home country, on worldwide revenue! To protect local companies that may be competing with you, some countries penalize you by inflating your bid price at the time of tender, making you less competitive, and then taxing you additionally on foreign exchange that you repatriate.

These are just a few of the considerations, too great to include in this publication, that you need to be aware of when considering operating in foreign waters. Needless to say, do your homework first.

Manpower/Industrial Relations

Immigration laws are one of the first considerations you must address when preparing to commence operations in a foreign country. All countries have clear policies relating to the use of foreign labor. Some are fairly open to this and others are very restrictive. In many cases, because of treaties or embargoes, some foreign nationals are welcome while others won’t get past the immigration desk at the port of entry. There are also income tax considerations when using foreign nationals.

Skilled labor exists in many of the world’s oil and gas producing regions, and in all cases you are encouraged to utilize the services of locally trained personnel. In some countries, the labor is unionized and operates under strict guidelines, set wages and benefits, and a standard rotation.

Many countries with an emerging oil and gas industry have a clear mandated policy of “technology transfer” requiring you to retain a minimum number of trainees onboard and a defined training program.

The successful international company will fully understand these conditions and laws, and use them to their advantage.

Quality/Certification

Certain companies, usually the more mature in our industry, require the ROV operator to maintain his business to high standards of quality that are auditable by the defining governing authority. This is generally a variable requirement dependent upon the country of activity, but can be worldwide policy for some of the larger oil and gas producers.

Standards such as ISO 9000 are commonplace these days, particularly in Europe and primarily in the North Sea. ISO 9000 is really just a system that requires the user to document all facets of its business carefully and thoroughly to ensure traceability and continuous improvement. The net result is supposed to mean improved overall performance and a safer working environment. Many companies, to their peril, can create a QA system that is ponderous and self feeding, stripping away the company's ability to perform and function efficiently.

Some countries have very strict regulations pertaining to the use of electronic and electrical equipment in an offshore environment, particularly when working in hazardous locations where gas or flammables may be present. In these instances, equipment must be rated to various standards of fire and explosion retardance. Equipment such as control and work vans that are man rated needs to be fabricated to standards to protect the occupants in case of fire or explosion. Vans will be built to A60 fire proofing and fitted with pressure locks, gas detection units and escape hatches to a certain standard (e.g., Zone 1 Div 1 Norway). This adds a significant capital increase to the equipment, which generally cannot be retrofitted.

Many companies view this as a safety requirement and specify this standard regardless of geographical location.

Contracting and Specifications

Approximately 80 percent of all commercial activities engaged in by ROV contractors are undertaken on daily rate basis. In the oil and gas industry, typically all drilling support is daily rate, while construction support and inspection may be either daily rate or fixed fee service.

As with all services, the Contractor is expected to enter into a contractual agreement with the oil company or other client. This contract will typically include the following articles as a minimum:

- Legal Description of the Parties
- Preamble
- Scope of Services
- Indemnities and Liabilities
- Insurance
- Term and Termination
- Schedule of Rates
- Application of Rates
- Specifications

These articles will be discussed in the following sections.

Legal Description

The legal description defines the parties who have entered into the agreement, includes contract information, state/country of incorporation, affiliates and subsidiaries.

Preamble

The preamble typically provides background information on the overall project. For example, it may provide a description of the facilities to be installed, pipelines and flowlines to be laid, determine the general contractor, location, water depth, timing of the project and any other pertinent general information.

Scope of Services

In the Scope of Services section, the complete scope of work of the ROV contractor is defined. It may come in a general form, which is typical in the Gulf of Mexico; or it may be in significant detail, which is generally the case in the North Sea and other regions.

The scope of work may be supported in the appendices of the agreement by procedures, drawings, WBS (work breakdown structure) or other relevant details. This is the “working” section of the agreement and the basis for the pricing structure of the contract.

Indemnities and Liabilities

All parties in a commercial agreement attempt to reduce their liabilities to the lowest level possible under the law. Since the ROV contractor does not maintain a very hierarchical position on the contractual food chain, the contractor will generally be expected to submit to indemnity and liability clauses that are prepared and "pushed down" by the oil companies.

Usually, the ROV contractor can expect to negotiate a "back to back' arrangement with the other party, whereby the contractor is not liable for damage to property or injuries of personnel of the other party. And, likewise, the other party is not liable for injury or death of the ROV contractor's personnel or damage or loss of the contractor's equipment. This is generally an acceptable arrangement, but it does mean that equipment damage by the negligence of the other party is the ROV contractor's problem.

Many clients require the ROV contractor to take on inordinate liabilities well beyond the scope of its services under the agreement and, in many cases, for issues that may not be insurable or may require the ROV contractor to purchase additional insurance.

Critical review of indemnity and liability clauses requires a professional eye. Insurance brokers usually provide this service as part of their annual fees and some larger ROV companies employ legal counsel either in-house or on a consultancy basis.

Insurance

Clients generally require certain minimum levels of insurance from their ROV contractor before work may begin. These are generally:

- Contractors General Liability (CGL)
- Workers Compensation
- Property and Plant
- Hired and Non-Owned Auto

On certain projects, additional insurance may be requested. For example, Hull and Machinery insurance when a vessel is chartered, or Builders Risk insurance when a large fabrication or installation project is under contract.

Minimum values are generally required under CGL and specified in the contract and, in most cases, the ROV contractor is required to name the client as additionally insured under the policy. Again, companies generally use the services of their insurance broker to aid in negotiating acceptable terms of insurance and levels of coverage.

Term and Termination

All contracts have a term of validity. Some may be for a period of years, such as Master Service Agreements, or days or months for "one off" style contracts. This is spelled out in the agreement and may be renewable upon mutual acceptance.

Termination is usually divided into two sections. The first is *termination without cause*, which allows either of the parties to terminate the agreement at will by giving sufficient notice. The second is for *cause*, whereby the party may terminate the agreement due to breach of contract or failure to perform. Typically, in this instance, the party under default or failing to perform will be given a number of days to remedy the breach or performance failure in order to avoid termination.

The parties will have remedies under the contract in the event of termination that may be very onerous to the defaulting ROV contractor, including paying for rework by an alternative contractor.

Schedule of Rates

The Schedule of Rates details the rates and fees billable by the ROV contractor for work performed under the agreement. It will typically include fees for mobilization and demobilization of equipment and personnel, daily rates for services such as equipment and personnel, fees for deliverables (reports, etc.) and any fixed fee services provided.

Application of Rates

The Application of Rates may form part of the schedule of rates, or be a stand-alone section. Basically, this section will determine the billing conditions and how the rates will apply. It will articulate when charges will commence, e.g., "upon completion of mobilization," determine what is included in the charges and will outline the service provided by the client under the agreement.

Specifications

Usually an appendix to the agreement, the Specifications section will include specifications of the equipment being provided, drawings, schedules and the tasks required to be completed under the contract.

CHAPTER 8. WHAT WILL THEY DO IN THE FUTURE?

The original “Operational Guidelines for ROVs” was written between the 1983 and 1984 ROV conferences by an exceptional team of experts in the field. In beginning to prepare Chapter 8 of this publication on the future of unmanned undersea systems, the original guidelines were reviewed as a baseline to help determine where this technology has actually gone. And, with a high level of curiosity, how well did that team of experts, 15 years ago, predict the future? Well, why should that decision be left only to our 1998 team of experts? Thus, we decided to do both. This chapter will include the original 1983 Forecast (under the 1983 heading) followed immediately by the 1998 update. The past and present comments will follow the original format for ease of comparison.

FORECAST

An Overview

1983

The past decade can clearly be characterized as the one during which ROVs have become operational, effective and accepted. The rapid acceptance, almost exponential, from a few modestly capable vehicles to many hundreds of ROVs is inexorably connected to the daily requirements of the offshore oil industry and, to a somewhat lesser extent, the military. It is most probable that the market profile for these vehicles has yet to reach the inflection point of the normal S-curve of growth. Therefore, with the normal risks of projecting into the future, an attempt is made to outline some of the likely issues and developments. One thing does seem clear, the demand for ROVs will continue to grow and their usefulness will expand as operational and economic demands force creative use of this relatively new tool.

This section of the guidelines will explore both operational and technological issues affecting the future use and acceptance of ROVs. In the process of anticipating future patterns in the ROV business, projections will be made of both needs for improvement or expansion of capability and of new developments likely to become available.

1998

The Overview section will be the easiest to comment on, and we couldn’t have said it any better, especially the following: “One thing does seem clear, the demand for ROVs will continue to grow and their usefulness will expand as operational and economic demands force creative use of this relatively new tool.” This “new tool,” however, has become an old friend to many of us working in the field. And, possibly to a few others, an old nemesis.

Observation

1983

The observational capabilities of ROVs will most likely continue to dominate their usefulness and acceptance well into the 1990s. The improvements sought will likely be evolutionary developments in technology, though major use of new technologies is likely in such areas as fiber optic cabled TV systems, and low light level TVs and cameras. The observational needs, in which improvements are needed are:

- Greater areas of coverage
- Higher quality TV images
- Enhanced object recognition
- Enhancement of real-time observational systems, both hardware and human engineering capabilities
- Improvements in non-real-time observational systems (i.e., film cameras, recorded high resolution TV, etc.).
- Improvements in the ease of locating the "camera" relative to the mission, so that more useful and rapidly acquired images can be obtained
- Improvements in documentation of vehicle operations, with emphasis on better information on path-track and vehicle orientation histories

The most likely developments to be obtained in improved observational capabilities include:

- New TV camera systems with higher resolutions, higher effective ASA ratings (low light capabilities), digital designs and more flexible optical systems (such as zoom capability)

- New and improved documentation, recorded in real-time, of the video and photographic systems. Powerful microprocessor and electronic systems will make this capability easy to program and change according to mission requirements

- There is likely to be elementary use of image enhancement techniques, first off-line and then a modest use in real time for the "topside" ROV operator. Powerful, low cost computers make this likely

- Modest improvements will be made in providing the operator with better path-track and vehicle orientation histories, though this is likely to continue to be a problem. The use of "instant-replays" and other existing video technologies will probably be tried on a wider basis

1998

There isn’t much debate about the previous observation forecast. As projected, the use of fiber optics has increased the bandwidth to allow the use of almost unlimited observation cameras and sensors. The advancements in the electronics industry, and the associated miniaturization, now provide fully digital cameras that can be diagnosed, and in some cases repaired, via modem by the factory. Advancements in low-light capability along with electronic still cameras also match the forecast.

Real time documentation of massive amounts of data, using optical discs and other mass storage devices, provides the operator with essentially more data that he can handle on site. For data that is used, advanced enhancement algorithms aid in the interpretation of the data. However, the forecast did miss on one item, at least slightly–the ease of programming. One of the detriments of ready access to massive storage is the trend to write inefficient programs–just look at the memory necessary for today’s software upgrades! On the other hand, the hardware developers have come a long way on the human factors end of the design cycle, and with touch screen displays and other user interface techniques, the operation of state-of-the-art hardware is becoming much easier for the user.

The knowledge of where your vehicle is located with regard to the ship, platform, ocean bottom, target, etc., has also come a long way, especially with the advent of accurate GPS coordinates as a starting point. Given the appropriate equipment, underwater navigation and tracking can be taken down to the centimeter level. This has enhanced the ability to accurately document underwater sites of interest, whether the *Titanic* or the *Challenger* debris field. It just gets down to the bottom line–how much do you desire to spend on navigation and localization aids. The technology is there.

So, where will the observation capabilities go in the future? As in many areas, the greatest strides have been made since the original forecast. Cameras are now miniaturized to the point they can be mounted within manipulator hands. New lighting systems add reality to underwater observations. Micro-navigation capability exists. The problem is that the law of physics can’t be changed. A photon is a photon and turbidity is turbidity. However:

- New techniques, such as laser line scanners, will push the envelop–they’re here now, albeit not cheep, and the developers are investigating techniques to optically scan the target while the laser is stationary. This will be an improvement over the existing method of moving the scanner. When the cost comes down, they will be a useful tool for many.

- Sonars have come a long way, but are also limited by the laws of physics. Their ability, along with some excellent data interpretation, to find long lost wrecks is exceptional. However, the penetration into the muck of the ocean bottom to find buried objects, whether gold bullion or mines or cables, requires advancement.

This will be a prime target for advanced computer analysis techniques and innovative applications of sonars and other sensors. The ability to see below the ocean bottom, with high resolution, is critical to many and is the next major challenge.

- And, to go out on a limb, the days of fame of *Robin*, *Jason Junior*, and other small tethered ROVs will go by the wayside as the new, acoustically controlled, underwater vehicle flies into harms way. Data will be sent back using expendable fiber optic cables, or acoustically, or it can be stored onboard and retrieved after the mission. Imagine the scenes that will be in "*Titanic II*" as the miniature vehicles search the hidden passageways of the ship, trying to uncover the answers to questions of the ages. Multiply the single vehicle into a team of interacting automatons, and the ability to observe large areas, inside and outside, will become a reality.

- Finally, the laws of physics will not change, regardless of the claims of some high tech marketeers.

Bottom Surveys

1983

The use of the tethered, free-swimming vehicles for bottom surveys will most likely continue to be restricted, in general, to smaller area surveys (like site surveys for an offshore platform). Pipeline surveys and wide area bottom surveys will continue to be dominated by towed ROVs. There will be exciting experimentation with hybrid towed/tethered, free-swimming vehicles. The *Argo/Jason* systems under development at the Woods Hole Oceanographic Institution is such an example. The *Argo/Jason* system offers great potential for geological/geophysical surveys for a wide area survey, where broad coverage with specific site reconnaissance is required.

There are likely to be attempts to broaden the area coverage of ROVs by extending optical and acoustic imaging capabilities. By increasing the distance between the lighting source and the camera (video or photographic), the improved area of coverage is dramatic. Experiments at the Woods Hole Oceanographic Institution project substantial improvements, possibly up to 1-4 acres/image. Such techniques, now planned for *Argo/Jason*, will slowly find their way into commercial systems.

Acoustic imagery (forward-looking sonar, side scan sonar, etc.) will likely be used more extensively. Yaw stability control will continue to limit the use of side-scan sonar. However, there are simulations and experiments underway which suggest that powerful sidescan imaging systems might be developed for tethered free-swimming vehicles.

These systems, likely to be a decade or more away, use side-scan data plus planned and measured yaw and track movements to develop 3-D images of the area insonified.

The improvements sought for bottom surveys will, most likely, be modest. While experimental systems such as *Argo/Jason* will lead the way to new capabilities, it will be a while before such systems are used on a wide-scale commercial basis. Improvements in untethered vehicle technology, combined with onboard data storage, will benefit this area in the future.

1998

The final statement of the previous forecast bears repeating. "Improvements in untethered vehicle technology, combined with onboard data storage, will benefit this area in the future." The 1983 forecast was accurate, and today much of the world's exclusive economic zones have been mapped with towed sonar systems with the expected 3-D plots now commonplace. However, in this case, it isn't necessarily the laws of physics that are the limiting factor, although they do constrain what can be accomplished and how fast, it is the cost of ship time that is critical. Saying that the world's oceans are vast is an understatement. The hardware is available to map the seafloor, or at least it can be easily built and purchased, but the financial commitment to do so is lacking.

Offshore, the use of unmanned underwater systems to survey areas is increasing, and with the reality and initial acceptance of AUV technology, the efficiency of such surveys will increase. Examples include the *Hugin* AUV now being used offshore, and the many AUVs being developed in academia, many with side scan sonar systems and other sensors that are performing exceptional underwater surveys, either storing the data onboard or sending it back acoustically.

What will the future hold?

- AUV survey systems will become commonplace, not only in offshore oil and communication applications, but also in the military and scientific arenas. Although still in an adolescent phase, their growth will once again be enhanced by the infusion of military funds that will not only miniaturize the onboard subsystems, but increase their reliability to acceptable levels. Combined with the cost-effective approach in academia, this technology will be fielded and should follow the track of the ROV, becoming commonplace within the next 15 years at they reach full maturity.

- Towed survey systems will continue to advance in data collection and interpretation, with advanced computers providing every conceivable method of analyzing and viewing the results.

- Will the funds suddenly appear to properly map and investigate the world's oceans? No–governments will continue to dump many orders of magnitude more funding into domestic and space programs, while they ignore the impending doom of the Earth's future–our great oceanic realm–until it will probably be too late to recover. This is one statement we hope will be proven wrong to the greatest extent possible.

NDT Inspection

1983

NDT inspection of underwater systems and inspection of offshore structures will, most likely, continue to drive the design of ROVs. The requirements will continue to dominate both the engineering and operational characteristics for tethered free-swimming ROVs. Legislated or legal requirements for inspection of underwater and subsea structures will provide the incentive for increasing use of ROVs, though good maintenance procedures for structural integrity and safety will also contribute to this requirement. Vehicle capabilities can be expected to improve with respect to operating in the environment (i.e., greater power and maneuverability and also with respect to the inspection technique and the quality of the inspection).

The increased use of ROVs for NDT inspection will start at a depth beyond diver capabilities and work back up to improve on diver-supported methods now used. Cost and considerations of the safety of the diver will dictate any replacement of diver operated NDT inspection protocols. The major limitation to extensive use of ROVs for NDT inspection inside the structural complex of offshore structures will continue to be tether entanglement. Therefore, there is likely to be experiments to improve tether management. This problem may remain relatively intractable; an inherent problem of tethered systems. Research is also expected on methods to eliminate the tether on certain types of inspection systems.

NDT inspection, particularly of offshore systems and structures beyond routine diver depths, is so attractive that substantial efforts are likely to be expended to improve NDT inspection technology for ROVs. Many of the observational technologies discussed earlier pertain herein as well. Further, as positional capabilities improve in ROVs (i.e., to locate and accurately position an ROV at a predetermined location), then underwater sensors and tools for NDT techniques will likely find expanded use; these include:

- Ultrasonic thickness measurement
- Vibration mode and signature analysis
- Magnetographic crack detection
- Probes to detect changes in electromagnetic (EM) fields and gradients
- Magnetometers and acoustic sub-bottom profilers to assess buried components (pipes, foundations, etc.)
- Manipulators to perform inspection tasks
- Structural cleaning, with technologies like cavitation and high pressure water jets

Improved and cost-effective observational capabilities and NDT inspection capabilities for ROVs are two keys to the expanded use of these vehicles. Therefore, ROV manufacturers are likely to continue to improve their products in this regard.

1998

The forecast was correct in predicting that the capabilities of ROVs will improve, along with the advancement of NDT products by the manufacturers. However, the idea that NDT would be driving the improvement was rather near-sighted. In fact, the drive to deeper depths, and the understanding that unmanned systems will be providing the work at that depth, not divers, has forced the offshore companies to enter co-design agreements with vehicle developers and operators. Such agreements are resulting in offshore installations that are designed to be installed and maintained through the use of robotic systems. The high power, multi-manipulator, work systems of today are now there to meet the challenge. They will continue to improve, but will not see the exponential increases in capability and reliability experienced during the last 15 years.

The idea that the movement into deeper waters, beyond diver depth, will force the development of better NDT techniques, which would then work themselves back into shallower water, was also insightful. This idea is not revolutionary, but evolutionary–as the techniques are refined, they will be used to replace divers as the overall task and situation dictate. Will divers be replaced? Not totally, however, in time, they will certainly be reduced in number, and will probably change places with their robotic friend within the next 20 years to become the “ROV buddy” or “backup” as the case warrants. Economics and liability concerns will force this to happen.

The problems of working within the offshore structures will continue for tethered vehicles, as stated, because entanglement of the tether is always a potential problem. Successful use will require the development of offshore platforms and equipment that will allow the system to navigate easily, overcoming the poor acoustic path associated with underwater platforms. Techniques that will allow tetherless systems, or those that carry their own short tether, to move to way points, possibly recharge or plug in a short tether for power and communication, will be developed. Add to this equation the potential impact of computer augmentation, where the entire structural design is stored in memory, and the unmanned system will be able to follow much more autonomous or semi-autonomous routines. The solution is in long range planning between all concerned–users and developers. The technology will not be the limiting factor–ingenuity, planning and commitment will be.

Diver Support/Monitoring

1983

The diver-assist vehicle is an attractive idea because it can:

- Provide continuous "topside" monitoring of diver operations and safety
- Provide "topside" with observational data independent of the diver

- Locate the dive site prior to deployment of the divers or enter areas of likely hazard prior to the diver
- Document the diver's work
- Provide the diver with added capabilities, tools, cameras, etc.

These factors, combined with the increased availability of ROVs, should dictate an expanded use of the diver/ROV team. The combined capabilities of divers and ROVs will be explored carefully by commercial and military operators. The range of activities for such combined systems will likely go from simple augmentation of the diver (e.g., carry additional tools, provide extra lighting, document the diver's tasks, etc.) to complex tasks that require a carefully developed symbiosis between the diver and the vehicle/topside operator (e.g., working hazardous environments, installation of new or upgraded underwater components of an offshore structure or system). The attractive features listed above will continue to drive the use of diver/ROV teams. This is an area where simple evolution of concepts and operational techniques will dominate the expanded use of ROVs rather than revolutionary breakthroughs in technology. Existing systems can be deployed as components of diver/ROV teams and effectively complete the demands of a mission, with a cost-benefit that appears to be attractive to operators. The fact that the ROV has come to assist the diver and not to replace him will be realized.

1998

“The fact that the ROV has come to assist the diver and not to replace him will be realized.” This forecast statement is very true in reality, but in practicality, there is more to the equation.

Offshore, the ROV has, and is, being used as a diver buddy and has performed all of the tasks mentioned above. And in the shallow water–diver realm depths–the ROV has not replaced the diver, although everything that can be cost effectively covered by remote intervention is certainly moving in a diverless direction. As mentioned in the previous section, the drive to deeper, non-diver, depths is the real forcing function. And, with the development of robotic intervention technologies and methods, there will be an impact on the diver as these techniques evolve back into shallower water.

Where the unmanned systems will play an ever increasing role is in the areas of hazardous diving conditions. Whether biological, nuclear, or just Mother Nature at her worst, the unmanned systems are replacing divers–and saving lives. This is one area where not even the divers–unless they went beyond the decompression tables a few too many times–will argue. Risk the ROV, not the diver. Life is–and will remain–a precious commodity.

Search/Identification/Location

1983

Search and identification is similar to bottom surveys, which are discussed earlier. The future trends in searching, locating, and identifying man-made objects are very similar to the trends of future developments in survey systems. The technologies are similar within the restricted regions around offshore structures. With improved video systems, manipulators, and acoustic survey tools, ROVs will be used more extensively to locate and identify:

- Specific components or subsystems of a complex offshore structure or system
- Lost equipment and materials, including ordnance and other military systems
- Confirm location and identification of objects located by other means (acoustic or magnetic)

The use of ROVs (tethered, free-swimmers) will, most likely, remain the tool that performs the fine-scale search and survey missions. Locating lost objects, with only gross-scale knowledge of possible location, is a task unlikely to be successfully accomplished by tethered, free-swimming ROVs. Towed systems (i.e., magnetometers, acoustics and cameras) are better suited for the large-scale search. The tethered, free-swimming ROV is best suited to "come in for the kill" stage of the search. Increased depth of operation and expanded sensor systems, both likely to be available in ROVs of the next decade, will likely expand their use in the search and identification of man-made objects in the oceanic environment.

Untethered or autonomous vehicles (AUVs) are likely to find expanded use for search/identification. These vehicles are likely to become commercially attractive within the next decade or so in applications where continuous real-time data are not required. While acoustic tethers for data transmission from free-swimming untethered vehicles are being developed, the first use of these vehicles is most likely to be similar to *EPAULARD* where data (photos) are taken and viewed post-dive. AUVs will increasingly use artificial intelligence (Al) technologies (e.g., expert systems and other knowledge engineering techniques), and therefore, it is likely that the AUV will make increased use of Al to search for known objects. Al techniques can classify objects; hence, such techniques can discriminate between known objects, such as a wellhead or a piece of military ordnance, and normal underwater debris and topography. Al techniques have the potential to substantially assist vehicle performance in unknown or unfamiliar environments where search and identification techniques are essential to mission success. The military implication for this capability will strongly influence the development of extremely capable AUVs. However, cost and complexity will limit their usefulness in the commercial world. The obvious goal of researchers in this field is to achieve a totally autonomous ROV, which will be a costly and evolutionary process.

1998

The previous comments that ROVs are not for search are very true, especially in the deeper depths. However, for inshore applications, there may be no other choice–but that is not the dominant area under consideration here. Offshore is the real concern, where the areas are vast, and lost objects tend to remain lost. And, as expected, the ROVs made it to full ocean depth with *CURV III* and *ATV* breaking the magic 20,000-ft (6,096-m) barrier within a week of each other, and Japan's *Kaiko* smashing that feat by reaching the bottom of the Mariana trench–over 37,000 feet (11,278 meters) deep. That record will stand forever unless one of the ROVs takes a shovel along.

The use of AUVs, as projected, is the most cost effective search technique. And, as projected, their use for search is still in the adolescent phase, since they are costly. But the costs are coming down. Reaching total autonomy is costly, and will only be met through evolutionary development, with academia–drawing upon government and military research–leading the way.

One comment that was near-sighted was the fact that AUVs such as *EPAULARD* would only provide post-operation photographic data. In fact, semi-autonomous systems, using acoustic communications–such as *AUSS*–can now provide real time slow scan television images, in high resolution color, and side-scan sonar data, to full ocean depths.

AI is not here yet–but it is coming. Such tools are presently helping searchers find objects through the application of image recognition and enhancement technologies, many of which are being exploited from the space program.

Will autonomous search systems be here in the near future? Well, the US Navy thinks so and is putting a lot of money on the line in the LMRS program to prove just that. Academia thinks so and has cost effective systems working autonomously at this time. Cost and complexity are limiting factors, as stated in the previous forecast, but not debilitating factors. The answer–a resounding Yes. Just as the flying eyeballs were finally accepted offshore, so will the AUV. First in academic and scientific programs, then in more expanded government funded programs, and eventually into the offshore market. Like the ROVs in the 1970s and 1980s, their use will grow exponentially towards the end of the first decade of the new millennium.

Object Retrieval

1983

ROVs historically have had limited payloads or lifting capabilities, i.e. 50 lb (23 kg) or so. Therefore, the trends of the past decade, with regard to object retrieval, will continue. ROVs will be components of integrated lift systems, where the ROVs play the role of rigger, observer/monitor, and retrieval assistant to a heavier payload retrieval system.

Therefore, new tools to assist retrieval are likely to evolve. In one approach, the ROV cage, with a substantial strength tether, is likely to become the lift system, while the tethered, free-swimming vehicle does the rigging for the retrieval. ROVs are likely to be used increasingly in the recovery of objects weighing a few pounds to large vessels or lost aircraft.

1998

Correct–but understated. ROVs have come a long way, especially in the strength of their design and the capability of the umbilicals and their terminations. Through the frame direct lift using the umbilical or cageless ROVs is now achievable and often used offshore. ROVs will still operate as described in the previous forecast, but they will play a larger role than just facilitator.

In the area or large object recovery, the ROV is playing an ever-increasing role. Aircraft, gold bullion, missiles, helicopters, ships and components, even part of the *Titanic*, have been recovered using ROVs. There is no depth that is beyond today's recovery limits. Today, the limit seems to revolve around man's inability to grasp the reality of how quickly the environment can ruin one's whole day. What else can explain the fact that the item to be recovered often makes it from the ocean bottom to the near surface, or surface, before falling back into the sea. The forecast for the future is thus:

- Man will begin to understand the dynamics of the ocean and concepts such as added mass, snap loading, pull out strength, ram tensioners, and ship dynamics. With the addition of common sense, and readily available technology, he will use the ROV efficiently in future recovery operations with an ever-increasing rate of success.

- James Cameron WILL NOT raise the Titanic for an upcoming sequel.

Activity Monitoring

1983

The monitoring of underwater systems by ROVs (e.g., NDT inspection, diver monitoring, maintenance and repair of sacrificial anodes, and assistance during construction and assembly of underwater structures or systems) will most likely increase during the next decade. Operators will seek additional capabilities for ROVs to quantify the data obtained during a monitoring mission (e.g., obtain data from a navigational system to precisely locate an object). Future trends discussed in observational capabilities pertain hereto. There is likely to be improved integration of future ROV designs and offshore structures/systems design to facilitate the monitoring of activities. For example, ROVs and structures are likely to be designed so that the ROV can easily attach itself to a wide variety of locations on the structure. Thus, monitoring can be done from a fixed location, easing the "topside" operators task and stabilizing the monitoring ROV, with the monitoring activities likely to continue to expand in usage.

The offshore underwater operator has historically wanted to have a "pair-of-eyes" at the work site. This need will continue to push ROV technology for on-site observational capability. Higher resolution video, wider areas of coverage, improved documentation, better man-machine engineering, and deeper operating ROVs will make the substantive difference in the use of ROVs to monitor a wide variety of underwater activities and missions.

1998

The previous forecast is correct and not time dated. The improvements mentioned have occurred, and will continue to evolve into more advanced systems and subsystems in the future as market competition increases.

Construction Assistance

1983

The components of construction assistance that ROVs most often provide are:

- Observation
- Site surveys
- Diver support and monitoring
- Activity monitoring
- Manipulation of small parts or systems

These are each discussed in previous sections. It is clear that as each of these capabilities improve, the use of ROVs in construction is likely to expand.

It is highly likely that ROVs using an increasing amount of robotics technology will evolve during the next decade. Standard heavy construction industry technologies, such as welding, drilling and fastening are all likely to find use on very specialized underwater robots. These robots will be ROVs of the tethered type, mainly to facilitate the delivery of power and control. Many of these functions are now possible, and it is projected that more of these ROVs will be designed and integrated into the construction industry. Computer-augmented work systems will continue to expand in capability and number of applications.

1998

Another accurate forecast, as verified by the many tasks and examples of operational capability given throughout this publication. And, as mentioned earlier, the requirement to move into deeper waters offshore will only increase the overall capability of unmanned underwater systems in the future. The robotic system is not the limiting factor–proper integration of it into the overall system is.

Drilling Assistance

1983

The offshore oil and gas exploratory drilling and completion mission is a major driving force for the expanded use of ROVs. The oil and gas industry has clearly spawned the growth and extensive development of the ROV industry. ROVs are likely to find increased use in the drilling programs of the oil and gas industry, with emphasis on:

- Increasing their depth of operation
- Designing ROVs to be compatible to very specific under water tasks that need to be completed during drilling operations
- Increasing manipulator dexterity and payloads
- Designing underwater systems to be compatible with ROVs, especially in the areas of inspection and maintenance
- Increasing the range of special tools available to the ROVs for highly specific underwater tasks
- Increasing the ROVs capability to work in hazardous or extremely difficult environments (e.g., Arctic or North Atlantic) or in very complex geometries (e.g., inside the densely designed cross-member supports of some offshore drilling platforms)

1998

Again, right on the mark. And as shown throughout this publication, the activity is being refined and the level of complexity increasing.

The one area that deserves comment is the last–ROVs working in hazardous environments and in complex structures. As mentioned earlier, this is a critical area for the application of unmanned systems and the vehicles will move into the more hazardous areas, especially if the ability to take a diver out of harm's way exists. Within the offshore structures the technology is not there yet, nor the potential for integrating unmanned systems for more advanced tasks. With some planning and proper investment, unmanned systems–both tethered and untethered–should be able to work anywhere within the environment of the offshore complex.

Scientific Reconnaissance/Sampling

1983

There are two somewhat paradoxical patterns evolving in the use of ROVs by the scientific community. First, scientists, like the survey industry and the military, have used towed vehicles for years. Each community has developed highly sophisticated systems. The deep towed vehicles of the Scripps Institution of Oceanography pioneered this concept in deep ocean geology and related geophysical sciences.

The *ANGUS* vehicle of the Woods Hole Oceanographic Institution has contributed extensively to the location of hydrothermal vents in the ridge structures of the two major oceans. Therefore, the towed vehicle has been and will continue to be critical to the ocean scientific community. From this base of towed vehicle technology is coming a new generation of ROVs, the hybrid vehicle, exemplified by the *Argo/Jason* system. it is simply a marriage of towed system technology with tethered, free-swimming technology. The technology of the ROV is just now being deployed in the scientific community. It is likely to expand.

The other side of the paradox is the fact that untethered and autonomous ROV technology has largely been the purview of the scientific community, with some recent developments in the military arena. It is interesting to note that it is only now in the mid-1980s that the scientific community is beginning to explore the capabilities of tethered, free swimming ROVs. Two factors seem to contribute to this fact:

- A substantial number of scientific missions either exceed the depth capabilities of ROVs or do not require them

- The cost of ROVs has exceeded the cost-benefits accrued for the scientific mission for which they are suited

The change for the tethered, free-swimmer came with the marriage of this vehicle with the established and highly capable towed vehicle. The impact of the *Argo/Jason* system upon deep ocean science is likely to be substantial.

The AUV is also likely to impact scientific reconnaissance and sampling. One can envision the use of AUVs for scientific investigations that can be remotely controlled from satellites to provide ground-truth information to large-scale remote sensing measurements and experiments. A data link between the series of AUVs and the command satellite would provide real-time data to a land-based monitoring facility and permit alterations in dive plans as warranted. Such vehicles could be powered by long term, high yield batteries. Untethered ROVs with onboard, lock-on acoustic navigation and long-life batteries could also be used to track fish individually or in schools; while concurrently recording data on migration routes, swimming speeds, water depth and temperature. Other trends include:

- The future will require more accurate placement and/or detailed sampling

- A good potential for multiple vehicle systems in mid-water for observation, etc., will be necessary

- Block funding might provide application/use of ROVs similar to the *ALVIN* program. This could help force acceptance/use. It is anticipated that ROVs will receive slow initial acceptance in the scientific community, similar to their acceptance by the oil industry

1998

The initial points to be made here are to refute the first comments, which have been overcome in the last 15 years. Today, depth is not a limiting factor for scientific investigations, and the cost of ROVs no longer exceeds the benefits that they return to the scientific community. Now, the larger systems are still costly, but there are many smaller systems, such as *Phantom*s and *MiniRover*s, that can be obtained. And, with proper financial backing, the ROV can become a tremendous investigative tool for scientific applications–just look at what MBARI is doing with their *Ventana* and *Tiburon* ROVs. In October 1998, The *Ventana* completed dive number 1,500.

Also, the impact of the *Argo/Jason* vehicle concept was overstated in the previous discussion. Although ROVs like Robin and Jason Junior have made headlines operating from manned submersibles, the towed vehicle/ROV is still no more commonplace than it was in 1983. Search is still done by towed systems, and in-depth investigations are performed by tethered ROVs.

The forecast regarding AUVs that use advanced batteries for long endurance missions while maintaining contact via satellite is still accurate, it just hasn't happened yet. Solar power is also being looked into as the Autonomous Undersea Systems Institute in the US and the Institute of Marine Technology Problems in Russia team to develop this unique AUV. The automobile industry is advancing battery technology, and the military is funding advances in fuel cell and other technologies. The satellites are there along with the desire to perform bottom and mid-water sampling for extended periods of time. And, demonstrations of satellite communication during real-time operations have been performed. As mentioned, cost is the driver and it will continue to be. The acceptance is there, and the cost will come down with academia pushing the envelope, and within the next 15 year increment, the earlier forecasts of this section should become true.

Regarding block funding, or any significant increase of funds towards ocean research, the only comment that can be made is–don't hold your breath. Europe is leading the way in this area with several consortiums developing vehicles to address future investigations, which is a good start, but still too limited. And, time will tell if the encouraging comments made by the United States President and Vice President during the 1998 Year of the Ocean meeting in Monterey, California, ever come to fruition.

Instrumentation/Hardware Installation/Recovery

1983

Manipulation and adaptive tools are the essential components of an ROV that is used to support the installation or removal of hardware (including instrumentation and sensors) on underwater systems and structures. Underwater manipulators on-board present ROVs are still very elementary in capability and design. This, in all likelihood, will change slowly as the demand for dexterous and flexible manipulators, while considerable, is not yet a large enough market to substantially improve the capabilities of these systems.

The nuclear manipulator, highly developed, is not easily transferred to underwater applications. New technologies, such as force-feedback and highly adaptive control strategies, will increasingly be used in ROV manipulators. Precisely placing and orienting ROV manipulators to accomplish a complex task will continue to be a problem for both tethered and untethered free-swimming vehicles. Modest changes will take place to improve the handling of instrumentation and to assist in hardware installation. It is more likely that standards will evolve during the next decade to enable ROVs to be compatible with the underwater structures and tasks. For example, zinc anodes and their attachment mechanisms are likely to be designed to mate with a compatibly designed ROV. Instead of using a general purpose manipulator on a standard general purpose ROV, a vehicle is likely to be designed specifically to do the zinc anode replacement task and hence, it will be designed at the same time and compatible with the anode attachment configuration. The same concept is likely to evolve in the installation and recovery of other major hardware components, including instrumentation.

1998

The most interesting comment from the previous forecast is “The nuclear manipulator, highly developed, is not easily transferred to underwater applications.” This is interesting because following the publication of the original guidelines, the offshore market had a downturn and many equipment suppliers, including companies such as Kraft and Schilling, turned towards the nuclear industry to apply their technology. This not only advanced the state-of-the-art in the nuclear industry, but advanced the capability and reliability of the manipulators. With the increase in offshore activity, these companies returned to the ocean environment with very capable systems. As described in the section on manipulators earlier in this publication, today’s technology is ready and waiting to solve the most complex tasks.

With the advent of ROVs mating to various tool skids, to include trenching systems, the capability forecast earlier is also at hand. Modern unmanned systems are performing very advanced underwater robotic tasks because of proper advance planning and system integration. Today’s ROVs have become “special purpose” through the use of attachable systems such as the tool modules, which can be configured for a given task. Gone are the days of the ROV that can only perform a single task, however, don’t expect that the days of an ROV that can do everything are here. They aren’t. The size, power, depth capability, etc., are all factors in the equation, and the wise shopper will match those with the expected tasks for the most cost-effective solution.

Geotechnical Measurements

1983

The ROV has been and will continue to be used for site survey and pre-construction evaluation of geotechnical properties of the seafloor. Remote geotechnical measurement (e.g., acoustic sub-bottom profiling) can and will continue to be performed from towed vehicles and, in some instances, by conventional and untethered ROVs.

ROVs and AUVs are still not used extensively for collecting bottom samples. Shallow cores and grab samples are obtained, but the ROV (tethered, free-swimming) does not appear a viable component in the geotechnical assessment business. Bottom crawlers are likely to find increased use, however, the evidence to support this opinion is sparse. The central problem is that many of the geotechnical sampling tasks can be done by platforms lowered to the bottom on a wire from a surface ship, the task does not necessarily demand the flexibility of an ROV.

1998

The following forecast is pretty much right on and little has changed regarding the stated logic. However, in the cases where scientific institutions have access to an ROV, the vehicle is performing almost every scientific task that can be hung onto its frame. Vehicles of all types exist, from bottom crawlers to AUVs, and they will be used for geotechnical measurement if the situation warrants, however, its hard to beat a simple sampler lowered from a surface ship, especially in deep water. Such a task will probably be overkill for an AUV, however, combine it with other sampling tasks, such as those envisioned for Woods Hole’s *ABE* vehicle, and long term *in situ* observation and sampling can be performed in the near future.

Mine Neutralization/Countermeasures

1983

As discussed earlier in this publication, the ROV is revolutionizing the approach to mine neutralization. Present sweeping techniques are becoming ineffective against modern mines, and the use of divers is both limited and dangerous. Therefore, most of the world's navies either have, or are planning for, the acquisition of remotely operated mine neutralization vehicles. Much in the same way that the offshore oil industry has accepted this technology "whose time has come;" so has the mine hunting community. Several systems are operational or under development. The following are some examples:

- The *PAP 104*, which has been sold in larger quantity than any other ROV, has been operational for slightly more than a decade. The vehicle, developed by the French company Societie ECA and used by many different countries, has now built a MK4 model with many improvements over earlier versions

- The *MIN* mine neutralizing vehicle is being developed for the Italian Navy for use on their new "Lerici" class mine hunters. The vehicle is being developed by the Italian SMIN consortium.

- The *PINGUIN B3* mine neutralization vehicle is being developed by the German MBB/VFW group. It is now being supported by the German Ministry of Defense with two models undergoing operating trials

- The Mine Neutralization System is being developed by the US Navy and will be deployed in the near future aboard the new class of MCM ships which are presently being built

- *PLUTO* is the smallest of the systems and is manufactured by Italy's Gaymarine Company

- Also, several other major vehicle manufacturers have indicated how their vehicles could be modified for mine neutralization roles

Obviously, the trend is up in the area of mine neutralization applications of ROVs. With the many different systems being developed, just as there are many different new mine hunting ships, it is unlikely that any one system is going to corner the market. The largest effect on mine neutralization system development, as indicated by the specialization of the systems previously mentioned, will be the operational requirements and specifications that will have to be met. These may also vary considerably depending upon the country concerned, the mission, and its timing and/or criticality. The bottom line is that this will be an exciting area of development in the future with many challenges available to those who desire to pursue them.

1998

"…this will be an exciting area of development in the future with many challenges available to those who desire to pursue them." That about sums it up. The previous list on mine countermeasure vehicles has increased with several players entering the picture, however, the number of different MCM vehicles available has not changed dramatically. The US Navy's Mine Neutralization System is now operational on all MCM ships, including the newer Mine Hunter Coastal (MHC) ships. However, because of the cost of the *MNS* system, only now is it going through upgrades that are considering such innovations as fiber optic umbilicals and state-of-the-art computers.

The approach to MCM is as varied as the size and cost of the different vehicles that are sprinkled throughout the world's navies. Yet, even with the understanding of what a simple mine can do to a complex ship, MCM budgets do not match the threat.

What does the future hold? Well, if the researchers have anything to say about it, future MCM will be taken over by the likes of small underwater “cruise missiles” that expend themselves when they find a mine. Or, in the near shore environment, where bottom mines are used, autonomous robots will enter the area in mass, an assault by robotic crab-like vehicles that search out and destroy the menace. Far out? – yes. Real? – well, successful demonstrations have been performed. The challenge will be in finding the mine; destroying it will be easier. Eventually, probably within the next 15 years, the fully expendable MCM robot will be fielded, designed to replace the “not too expendable” systems that exist today. Production costs will be a driving factor (assuming the performance is there) because there will need to be a large number of these robotic systems. As stated earlier, “this will be an exciting area of development in the future with many challenges available to those who desire to pursue them.”

Maintenance/Repair

1983

The routine maintenance and repair of offshore systems and structures will require ROVs specifically designed for that purpose, and compatible with the structure or systems, much like the zinc anode concept discussed earlier. Manipulators with extensive tool packages will continue to find use, and modular repair/maintenance packages are likely to evolve. In the past, maintenance techniques have not been a component of the structure/system design. The trend is likely to be one in which an ROV is designed to be compatible with a system/structure that has been designed to receive the maintenance and repair system contained within an ROV.

Deep-water offshore structures and systems will "drive" this design concept. The types of maintenance tasks in which ROVs will be used with more frequency include:

- Ring replacement
- Flow-line inspection
- Valve turning
- Hydraulic override
- Control pod replacement assistance
- Check condition of corrosion protection
- Detailed structural inspection
- Cleaning/jetting tasks
- Anode replacement

1998

On the mark, but today's systems have gone even further, especially in their offshore role is subsea completions. As discussed earlier, and throughout this publication, the trend offshore is towards the modular system that can work with various work or tool modules, which have been designed specifically to interface with the underwater structure. The days of the "special purpose" ROV are going by the wayside, and intelligently designed systems are coming into play. Deep water applications are driving this area, and remote systems will evolve to meet the task at hand. The challenge is up to the designers, it will NOT be limited by technology.

Positioning/Navigation

1983

The area of ROV positioning and navigation is one of the ROV technology areas that needs attention. Historically, ROVs have used a TV to permit the Topside ROV operator to navigate the vehicle. The need for a 3-D positioning/navigating system is critical, particularly inside complex structures.

Research is being conducted on this problem, and highly redundant acoustical systems seem the most likely candidates for near and within structural navigation. Experiments at several laboratories suggest that such acoustical systems can be used in and near complex offshore structures. It is likely that these systems will be deployed on a limited basis for commercial and military applications during the next decade.

1998

Unfortunately, research is still being conducted on the "within structure" navigation problem. As mentioned earlier, the solution will probably be provided through some unique applications of technology, robotics, computer-assisted navigation, etc. Underwater acoustics is driven by the laws of physics and that will have to be lived with. Research will continue, and eventually, the problem can be solved–but it will not come easily.

As for the out of structure environment, the needed accuracy is available. It's a matter of properly designing it into the system, as mentioned earlier in this publication.

Arctic Applications

1983

The Arctic, as it becomes more important to the oil and gas industry and to military defense, will provide a fertile environment for both tethered and untethered systems. For example, a recent study (1983) to determine the usefulness of ROVs and AUVs for measuring under ice topography and roughness suggests that tethered, free-swimming ROVs might be useful for a coverage up to about one square mile. This is but one application of ROV technology.

There are several research efforts to extend ROV technology to Arctic applications. The University of Washington *UARS* vehicle is one such experimental ROV. The *AIMS* vehicle of the University of New Hampshire is another. Both of these are designed for experimental efforts, with little likelihood of commercial applications in the near future.

There is considerable interest in placing side-scan sonar systems aboard an ROV (probably untethered) to expand the capability to evaluate under ice structures and seafloor topography. It is likely that these experimental vehicles will continue to evolve.

1998

This is one area that has gone beyond the forecast. ROVs and AUVs have been used many times in the arctic for both scientific and military oriented missions. Tasks such as running lines from one ice hole to another to allow installation of instrumentation or arrays have been performed. And, to top them all, the recent *Theseus* mission, where a long distance fiber optic cable was taken from the shore to deep water, proves the potential usefulness of such systems in the arctic environment. Only time and one's imagination will determine how many other useful tasks will be conducted in that hostile environment. However, be forewarned–some of the environmental conditions in the arctic can make an offshore platform in the middle of winter look good.

ROV Design and Capabilities

1983

As the usefulness of ROVs becomes wider, the vehicles themselves will become more widely capable, and the distinction among various types described earlier will become blurred. Tethered vehicles will swim to structures and attach themselves to use the structure itself as the positioning medium. Towed vehicles will incorporate thrusters so that their tracks can be controlled more closely in deep water. Towed and free-swimming vehicles will be able to land on the bottom to make geotechnical measurements, take samples and install instruments. Tethered, free-swimming ROVs will be adapted for research in deep water in systems like *Argo/Jason*. In the scientific research arena, the applications will combine to carry out deep ocean tasks now performed by manned submersibles, or not performed at all.

Each of the following major areas of ROV technology will, within this decade, likely see the evolutionary changes as indicated:

Technology Area	Comments
• Vehicle structure	Modest engineering improvements likely but no new major developments
• Vehicle ballasting	Modest engineering improvements likely but no new major developments
• Vehicle propulsion	There will likely be new ideas tried
• Electrical power	Modest engineering improvements likely, but no new major developments
• Vehicle control and navigation	Considerable effort is expected to improve these capabilities
• Manipulators	Improvements will be seen, especially in computer-augmented controls
• Tools and sensors:	
- Video	Substantial improvement likely
- Still cameras	No major changes likely
- Cine cameras	No major changes likely
- NDT devices	Considerable innovation likely
- Current sensors	New ideas likely to be tried
- Acoustic sensors	Considerable innovation likely
- Leak detectors	Modest improvements likely
- Cleaning devices	New ideas likely to be tried

-	Vehicle immobilization devices	New ideas likely to be tried
-	Work tools	New ideas likely to be tried
-	Scientific instruments	New ideas likely to be tried
-	Cables and pipe tracking	Improvements very likely

Manipulation improvements will likely receive particular attention in this decade. It is conceivable that we will see the incorporation of a sense of touch for manipulators, which will be combined with supervised sensory controls and computer graphics capabilities. This will permit the ROV to "feel an object in water of zero visibility. The computer will then generate a graphic display of that object from sensor input and a prior knowledge (memory) of the object's configuration, dimensions and texture. By checking a reference point the object can best be kept "in view" through use of the computer graphics programming. Manipulators may be equipped with sensors that can track their motions and redraw them on the display to enable the operator to perform tasks on the object without ever visually observing it. Video updates, when possible, would permit confirmation of the operator's perception of the object.

It is always risky to predict developments in the future. It does not appear that operational requirements and economic attractiveness will continue to push the design and development of ROVs. However, the ROV of the 1990s is very likely to make the current systems look very modest in capability and in engineering sophistication.

AUVs, while not a central theme to this manual, will play an increasingly important role in the broad field of ROVs.

When the power and communication tethers to an unmanned underwater vehicle are no longer necessary, many new opportunities for working and exploring in the ocean are created. The potentials are matched by the new problems that result.

The key to the growing interest in untethered vehicles is the fact that, as the depth of operation of an ROV substantially increases and as the range of operation is extended, the drag imposed by the tether becomes a major limitation. The thrusters, and thus the vehicle itself, must become larger, the cable thicker, and the energy expended in cable tending grows rapidly. The required shipboard handling facilities become massive as depth and range increase, and an economical limit is reached. Three major consequences result if extended range requires operating without a cable:

- All energy now required for the assigned task must be carried onboard at the start of the mission

- Communications become tenuous and man-machine interactions become difficult when an acoustic channel must be used

- Increasing reliance must be placed on onboard intelligence to fulfill assigned tasks

Not all tasks assigned to an underwater vehicle, particularly at greater depths and ranges, entail substantial amounts of manipulative work. Among these missions may be included the following:

- Search and survey, in deep water and at extended range

- Deep ocean science

- Under ice mapping, survey or transport

- Offshore petroleum system inspections where water depth, concern for safety, fear of entanglement, or the need to work within a structure makes tethered ROVs or manned submersibles undesirable

- Military interests

Freed of the burden of the tether, the entire energy budget of the vehicle is much reduced. In most of these classes of tasks the constraint of carrying an onboard power supply capable of an extended assignment appears not to be a major system limitation. Robotic, untethered vehicles of very modest size, and quite suitable for davit launching, have been projected that possess design ranges of 1,000 nautical miles or more, and endurances in excess of one week.

The removal of the tether would have been quite impossible before the advent of the microprocessor, and it is only the possibility of incorporating machine intelligence in the vehicle that makes consideration of tether removal possible. Today, machine intelligence comparable to the largest fixed computer facilities available when the early ROVs appeared is available in a size entirely compatible with a very small submersible. Memory is inexpensive, computing speeds are high, and as a consequence, a remarkable amount of machine intelligence is available to an untethered automaton. The key problem involves putting that intelligence to work in an effective manner.

A wide range of technologies converge in the development of an autonomous ROV. It is clear that not all the necessary skills are in place today to assure that more than simplistic missions may be accomplished, and certainly much research remains to be done. The pacing technologies that control the potential for effective untethered vehicles appear to include:

- Knowledge engineering
- Computing systems - hard/software
- Navigation
- Communications
- Power sources
- Deployment and logistics

The removal of the tether, which supplies power and communications, creates major technical issues, but generates an opportunity to perform tasks quite impossible for the conventional ROV. The achievements of operational systems such as the *EPAULARD* have demonstrated the versatility and reliability of the untethered vehicle in simple, yet important missions. The research now underway is being conducted in over a dozen universities and industries, and gives evidence of the difficulty, as well as the promise, of the intelligent untethered vehicle. It is quite evident that such machines will not soon take over many ROV tasks, and indeed, they probably never will. Progress in this parallel field, however, has been extremely rapid, and, indeed, a substantial transfer of technology back to the ROV could be a major consequence of the ongoing studies.

1998

Taking a look at the previous forecast, the biggest understatement was “the ROV of the 1990s is very likely to make the current systems look very modest in capability and in engineering sophistication.” Modern work class systems are not only impressive, but are approaching awesome. Their potential is only limited by the team of engineers and planners that are integrating them into the future.

As far as subsystem projections, again, they were basically correct. As expected, the area of manipulators has seen great strides, and although the realm of total computer graphics of the undersea site hasn’t really been reached offshore, it has been achieved in the laboratory. The technology is there to create an autonomous work environment–it is up to the engineers to incorporate it.

The impact of the *Argo/Jason* technology–a vehicle with a smaller ROV operating from it for detailed inspection–was never as dramatic as thought from the 1983 perspective. However, the secondary ROV concept has certainly been embraced, and ROVs have been working from manned submersibles in the filming of many excellent underwater movies and documentaries. In addition, the ability for the ROVs to not only reach the ocean depths of 20,000 ft (6,096 m) and beyond, but to be able to work there, has been demonstrated and exists when needed–a fact not embraced overwhelmingly in the forecast.

Interestingly, no where in the forecast did anyone ever project the impact of underwater robotics on the movie industry. Films like the *Abyss*, with their robotic co-stars like "*Little Geek*," made for great entertainment for those of us in the industry. And, speaking of filming, or just seeing underwater, the forecast of "substantial" improvements in the video and photographic areas was also on target. Today's ability to see well underwater (enhanced by both TV and lighting), which provides the means to manipulate and work reliably, has been an essential ingredient for the rapid progress in the work class vehicle.

The potential for the AUV made in the forecast was mixed–both seemingly positive for the technology in some cases, and not so in others. Acoustic communications has progressed further than expected–the vertical link has been proven reliable, and the horizontal link is extending further as research continues in the field. As stated, "The key problem involves putting that intelligence to work in an effective manner," and this won't change any time soon. Afterall, if an AUV is to be autonomous, the problem of onboard intelligence had better be solved. The comment that "It is quite evident that such machines (AUVs) will not soon take over many ROV tasks, and indeed, they probably never will," was a little pessimistic, depending upon which tasks are being addressed. AUVs are reaching the point on the development curve where their use for offshore and scientific tasks is beginning to increase at an exponential rate. The "davit launched" system is at hand in the universities and they are diving to 20,000 ft (6,096 m). The AUV has come a long way since the *EPAULARD*.

Another critical point missed in the forecast regarding the vehicles overall was their increase in reliability and their final acceptance into virtually all aspects of underwater work and investigation.

Where will the design of ROVs go in the future? Well, the comments of the previous forecast are still applicable. Evolutionary improvements can be expected in most areas. The potential for robotic intervention, with computer generated environments, exists and will eventually be seen offshore as developments move into deeper water. Remote intervention is not a choice, it is mandatory, and this will drive further advancements in systems and subsystems across the board.

General Comments

1983

Some concluding thoughts seem appropriate to a section on the "Future."

ROVs will likely be used in the support of other ROV operations, such as a second vehicle overviewing the operation of the first vehicle. In some cases this may be combined with an active garage or cage where the garage has TV, lights, and possibly propulsion. Dual ROV operations have already been tried and are likely to expand in acceptance.

ROVs can be expected to see increasing use as a backup safety system for the operation of manned submersibles. For example, when the manned submersible is in a compromising position, the ROV will be dispatched to observe the situation, identify the problem and assist in rescue or recovery.

The use of ROVs with self-contained power and expendable, deployable control cables, either fiber optic or small wire, will appear. This will be the transition vehicle to wider use of untethered or autonomous ROVs. The untethered ROV operation in a complex structure could be a one way trip, that is, down…around…in and out…then to the surface for recovery. The untethered ROV would not have to retrace its steps to return. This is also a very suitable approach for water flow tunnels.

Incorporation of fiber optic or laser gyroscopes will provide vastly improved performance and increase the lifetime of inertial guidance systems. Currently, navigation near platforms requires mechanical gyros with short (1,000 hour) lifetimes.

These and other developments will increase the use and acceptance of tethered, free-swimming ROVs. They will continue to grow in their capabilities, and when the user understands these capabilities and their limitations, he will begin to design his underwater equipment for installation, inspection and maintenance by ROVs. The next major milestone will be when the users of ROVs and the designers of underwater structures jointly develop deep water, remotely maintained systems. This, together with subsequent advances in ROV manipulation, control, and work tools, will produce great strides in the performance of "real" underwater work. Hopefully, this publication will provide the baseline knowledge to fuel this evolution

1998

How could we have said it any better in 1983 than “They will continue to grow in their capabilities, and when the user understands these capabilities and their limitations, he will begin to design his underwater equipment for installation, inspection and maintenance by ROVs.” This was prophetic back then, and should be the cornerstone of the future. Nothing has changed in the implications of that statement.

Operations using multiple ROVs have become commonplace offshore, as projected, with as many as four work class ROVs working on a deepwater project. And, they are not alone–research into using multiple AUVs, although not for offshore applications yet, is high on the agenda. The use of multiple AUVs will probably evolve into reality within the next 10-20 years as advancements in onboard intelligence and underwater communications continues to progress. Their potential for mine countermeasures, aided through the military’s financial backing, will help advance this technology.

Rescue of manned submersibles by ROVs did progress. Vehicles such as the *Kaiko*, which will provide the potential for rescue of the *SHINKAI 6000* submersible from beyond its crush depth, have been developed. What will probably be seen in the future is the replacement of systems such as the US Navy's manned submarine rescue vehicles, the DSRVs, by large ROVs. The technology is there to use.

And, as projected, fiber optic communication links have been developed and are in use by the military for many applications. Unfortunately, their cost is high, which may keep such expendable communication links out of the oceanographic market.

THE FUTURE?

The theme of the first ROV conference in 1983–"A Technology Whose Time Has Come"–pretty well sums up the unmanned undersea vehicle industry during the last 15 years. Not only has it come, it has rocketed into a critical technology for ocean work and exploration in the future. Where it will go in the future will be driven by one concern, both of which revolve around the "bottom line."

Offshore, the "need" will drive their integration into future developments, primarily because that will be the only way to get the oil needed in the future–no unmanned systems…no oil…no profits. Bottom line.

The military will continue to spearhead the technology as it seeks more efficient, and often covert, means to perform its missions. Mine countermeasures will be one of the most often discussed issues. However, if the past is any indication of what to expect in the future, the "bottom line" will be higher on more dramatic programs such as satellites, cruise missiles, etc., and MCM will continue to be only a bridesmaid.

Will the governments up their "bottom line" and invest into the world's future, if not its survival? So far, there has been plenty of talk, but relatively little financial action; at least when compared to other worldly investments. Time will tell if the funding will come, however, don't count on it–at least not to the level that it is needed.

Luckily, the "bottom line" that will provide the most dramatic impact will be the academic budget. With notoriously little funding in the past, and no expected changes in their financial picture in the future, they will develop the technology with cost effectiveness in mind. Low cost, expendable systems (maybe not for the university) will be developed. With that, the first steps into exploring the world's oceans will be at hand. As these unmanned underwater systems expand in number and use, the dramatic gains in data and understanding will just add fuel to the fire. But, their acceptance as a cost effective tool by potential users will only be the first step.

The most critical step will be when their loss becomes acceptable. Only when the community can field unmanned systems in numbers that allow acceptable losses will such systems finally reach their potential. This critical step should approach reality within the next 15 years. And, this cost effective approach will also roll over into the LCROV area, where they will continue to expand in acceptance and use throughout the world's shallower water–and in some cases deep water–environments.

The future is a design problem. The technology is there, or will be, to allow us to perform virtually any task desired underwater. This publication is proof of that. And, as discussed above, the use of unmanned underwater systems will be driven by the bottom line. Accordingly, the potential for unmanned underwater systems in the future is under our control. The choice is ours.

APPENDIX A. LIST OF ACRONYMS

ABS	American Bureau of Shipping
AC-1	Atlantic Crossing Cable System
ACMA	Atlantic Cable Maintenance Agreement
ACMV	Advanced Cable Maintenance Vehicle
ADC	Association of Diving Contractors
ADCP	Acoustic Doppler Current Profiler
AI	Artificial Intelligence
ALUV	Autonomous Legged Underwater Vehicle
AM	Amplitude Modulation
AODC	Association of Offshore Diving Contractors
APII	All Purpose Intervention Interface
ASA	American Standards Association
ASW	Antisubmarine Warfare
ATD	Advanced Technology Demonstration
ATV	Advanced Tethered Vehicle
AUSS	Advanced Unmanned Search System
AUV	Autonomous Underwater Vehicle
B&W	Black and White
BOP	Blow Out Preventer
Bps	Bits per second
CB	Center of Buoyancy
CCD	Charge Coupled Device
CCTV	Closed Circuit Television
CG	Center of Gravity
CIF	Common Interrogation Frequency
CMROV	Cable Maintenance Remotely Operated Vehicle
COMPATT	Computing and Telemetering Transponder
COTS	Commercial Off-The-Shelf
CP	Cathodic Protection or Potential
CTD	Conductivity, Temperature and Depth
CURV	Cable Controlled Underwater Recovery Vehicle
CVI	Close Visual Inspection
DARPA	Defense Advanced Research Projects Agency
DAVID	Diver Assistance Vehicle for Inspection Duty
dB	Decibel
DFCS	Diverless Flowline Connection System
DGPS	Differential Global Positioning System
DNV	Det Norske Veritas
DP	Dynamic Positioning
DSP	Digital Signal Processing
E&P	Exploration and Production
EEZ	Exclusive Economic Zone

EHF	Extra High Frequency
EHF	Extremely High Frequency
EMI	Electromagnetic Interference
EMO	Equipment Movement Order
EOD	Explosive Ordnance Disposal
ETP	Electrolytic Tough Pitch Copper
EWT	Extended Well Testing
FDM	Frequency Division Multiplexing
FLAG	Fiber-Optic Link Around the Globe
FM	Frequency Modulation
FSB	Fish Bite Protected
Fsw	Feet of Seawater
FTS	Flight Telerobotic Services
Gbps	Giga-bits per second
GFI	Ground Fault Interrupt
GIFS	(Computer Icons)
GII	Global Information Infrastructure
GPS	Global Positioning System
GRP	Graphite-Fiber Reinforced Plastic
GVI	General Visual Inspection
HF	High Frequency
HPU	Hydraulic Power Unit
Hz	Hertz, measure of frequency (cycles per second)
ICCD	Intensified Charge Coupled Device
ICPC	International Cable Protection Committee
ICS	Integrated Control System
IMCA	International Marine Contractors Association
IMR	Inspection, Maintenance and Repair
IOC	Initial Operational Capability
ISIT	Intensified Silicon Intensified Target
JAMSTEC	Japan Marine Science and Technology Center
kHz	KiloHertz
kPa	Kilo-Pascals
KST	Korean Submarine Telecom
LAN	Local Area Network
LARS	Launch and Recovery System
LBL	Long Baseline
LCE	Linear Cable Engine
LCROV	Low Cost Remotely Operated Vehicle
LF	Low Frequency
LLS	Laser Line Scanner
LMRP	Lower Marine Riser Package
LMRS	Long-Term Mine Reconnaissance System
LOP	Line of Position
MAUV	Multiple Autonomous Underwater Vehicles
MCM	Mine Countermeasures

MF	Medium Frequency
MHC	Mine Hunter Coastal
MHz	MegaHertz
MLO	Mine Like Object
MMS	Minerals Management Service
ms	millisecond
Msw	meters of seawater
MTS	Marine Technology Society
MUX	Multiplex
NASA	National Aeronautics and Space Administration
NBPLSS	Neutral Buoyancy Portable Life Support System
NDI	Non-Developmental Item
NDT	Non-destructive Testing
NEC	National Electric Code (US)
nm	Nautical Mile
NMRS	Near-Term Mine Reconnaissance System
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NTSC	National Television Systems Committee
NURP	National Undersea Research Program
OIM	Offshore Installation Manager
ONR	Office of Naval Research
OSHA	Occupational Safety and Health Administration
PAL	Phase Alternated Lines
PAN	Programmable Acoustic Navigator
PEM	Proton Exchange Membrane
PFE	Power Feed Equipment
PUV	Programmed Underwater Vehicle
PVC	Polyvinyl Chloride
R&D	Research & Development
RCV	Remotely Controlled Vehicle
RECON	Remotely Controlled Undersea Vehicle
RF	Radio Frequency
RFI	Radio-frequency Interference
RGB	Red Green Blue
RMOP	Remote Minehunting Operational Prototype
RMS	Remote Manipulator System
ROMV	Remotely Operated Maintenance Vehicle
ROT	Remotely Operated Tool
ROV	Remotely Operated Vehicle
RPV	Remotely Piloted Vehicle
SDH	Synchronous Digital Hierarchy
SBL	Short Baseline
SECAM	Sequential Color and Memory
SIT	Silicon Intensified Target
SL	Signal/Source Level

SNR	Signal to Noise Ratio
SPDM	Special Purpose Dexterous Manipulator
SPL	Sound Pressure Level
SPS	Subsea Production System
SPURV	Self-Propelled Underwater Vehicle
SSB	Single Sideband
SSBL	Super Short Baseline
SSVS	Sonar Scour Vision System
SUT	Society of Underwater Technology
SVP	Sound Velocity Profile
SWAP	Sweep Within A Pulse
TAT	TransAtlantic Telephone (cable)
TCA	Task Complexity Algorithm
TDM	Time Division Multiplexing
TL	Transmission Loss
TLP	Tension Leg Platform
TMS	Tether Management System
TREC	Tethered Remote Camera
TUUV	Technology for Unmanned Underwater Vehicles
UAV	Unmanned Air Vehicles
UHF	Ultra-High Frequency
UROV	Untethered Remotely Operated Vehicle
UT	Ultrasonic Thickness
USBL	Ultra Short Baseline
UUV	Unmanned Undersea Vehicle
VB	Variable Buoyancy or Variable Ballast
VHF	Very High Frequency
VLCROV	Very Low Cost Remotely Operated Vehicle
VLF	Very Low Frequency
VOS	Vectored Orientation System
Vp	Speed of Sound in Water
VRU	Vertical Reference Unit
WAN	Wide Area Network
WOW	Waiting on Weather

APPENDIX D. EDUCATION AND RESOURCES

This appendix provides information regarding academic institutions, professional societies, and other potential sources for education or information in the area of unmanned underwater systems.

INSTITUTIONS

The following listing identifies academic and scientific institutions involved in the development of unmanned undersea system technologies. Many references come from technical presentations at recent conferences by professors and students. Addresses are provided to the extent information was available. For additional information, the reader is encouraged to contact the institution of interest directly. Where available, the internet web page is provided.

- Applied Physics Laboratory, University of Texas, U.S.

- Autonomous Undersea Systems Institute, 86 Old Concord Turnpike, Lee, NH 03824.

- Brigham Young University, Department of Mechanical Engineering, Provo, UT 84602

- California State Polytechnic University, Pomona, College of Engineering, 3801 W. Temple Ave., Pomona, CA 91768.

- Cambridge University, U.K.

- Carnegie Mellon University

- Centre Technique des Systemes Navals - Dissuasion Lutte Sous-Marine, BP 28, 83800 Toulon Naval, FR.

- Charles Stark Draper Laboratory Inc., 555 Technology Square, Cambridge, MA 02139.

- Democritus University of Thrace, TK 67100, Xanthi, Greece. POC: J.N. Lygouras

- Florida Atlantic University. Contact the Department of Ocean Engineering, FAU, 777 Glades Road, Boca Raton, FL 33431. Phone 407-367-3435; http://www.oe.fau.edu/general-info.html.

- Florida Institute of Technology, Division of Marine and Environmental Systems, 150 West University Blvd, Melbourne, FL 32901-6975. Phone 407-768-8000, x8096.

- Harbor Branch Oceanographic Institution, Inc., 5600 US 1 North, Ft. Pierce, FL 34946, U.S., <www.hboi.edu/engineering/rov.html>
- Heriot-Watt University, Department of Computing and Electrical Engineering, Edinburgh, EH14 4AS, Scotland, UK.
- IFREMER, Subsea Robotics Laboratory, BP 330, 83507 La Seyne-sur-Mer Cedex, France.
- Institute of Marine Technology Problems, Russian Academy of Sciences, Far Eastern Branch, 5a Sukhanov Str., Vladivostok, 690600, Russia.
- Institute of Ocean Sciences, Sidney, BC, Canada.
- Instituto de Sistemas e Robotica - Porto and Instituto Superior de Engenharia do Porto, Rua de S. Tome, 4200 Porto, Portugal
- Instituto Superior Tecnico, Institute for Systems and Robotics and Department of Electrical Engineering, Av. Rovisco Pais, 1096 Lisboa Codex, Portugal.
- Japan Marine Science and Technology Center, 2-15, Natsushima-Cho, Yokosuka 237 Japan.
- Jardfraedistofa of Iceland
- Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109.
- John Hopkins University, Department of ME, 123 Latrobe Hall, 3400 North Charles Street, Baltimore, Md 21218.
- Kyushu University, Japan.
- Laboratoire d'Electrotechnique et da Magnetisme de Brest, Ensieta, 2 rue F. Verny, 29806 Cedex 9 FR.
- Linkoping University, Sweden
- Massachusetts Institute of Technology, Cambridge, MA 02139. AUV Laboratory or the Sea Grant College Program, 292 Main Street, E38-300, Cambridge, MA 01239
- Meiji University, Department of Mechanical Engineering, School of Science and Technology, 1-1-1 Higashi-mita, Tama-ku, Kawasaki 214 Japan.

- Memorial University of Newfoundland, Ocean Engineering Research Center, St. John's, Newfoundland, Canada A1B 3X5.

- Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, CA 95039-0628. www.mbari.org.

- National Taiwan University, Dept. of Naval Architecture and Ocean Engineering, 73 Chou-Shan road, Taipei, Taiwan, Republic of China

- Naval Postgraduate School, Monterey, CA 93940. Dept of ME. www.nps.navy.mil.

- New Castle University (England)

- North Carolina State University, Raleigh, NC.

- Northeastern University, Department of Electrical and Computer Engineering, Boston, MA 02115 or Marine Systems Engineering Laboratory, East Point, Nahant, MA 01908.

- Norwegian Institute of Technology, N-7034 Trondheim, Norway. Professor K.E. Malvig.

- P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, Krasikova 23, 117218, Moscow, Russia.

- Princeton University, Department of Mechanical and Aerospace Engineering, Princeton, NJ 08544.

- Royal Naval Engineering College, Manadon, Plymouth, UK PL5 3Q.

- Santa Barbara City College, Santa Barbara, CA., U.S.

- Shenyang Institution of Automation, AI Lab, Chinese Academy of Sciences, 114 Nanta Str., Shenyang 110015, P. R. China.

- Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6..

- Scripps Institution of Oceanography, Marine Physical Laboratory, University of California, San Diego, CA.

- Southampton Oceanography Centre, Empress Dock, Southampton SO17 1BJ, UK.

- Southampton University (England)

- Stanford University, Aerospace Robotics Laboratory, Durand Building 250, Stanford, CA 94305.
- Technical University of Denmark, Building 326, DK-2800 Lyngby, Denmark.
- Technical University of Nova Scotia, Halifax, N.S., Canada B3J 2X4.
- Texas A&M University, Galveston, Texas, U.S.
- Texas A&M University, Computer Science Department, College Station, TX 77843-9284.
- The Center for Marine Science and Technology, Curtin University, Australia.
- The Pennsylvania State University, Applied Research Laboratory, Post Office Box 30, State College, PA 16804-0030.
- The University of Calgary, Department of Mechanical Engineering, Calgary, Alberta, Canada T2N 1N4.
- The University of Connecticut at Avery Point.
- The University of Liverpool, Department of Electrical Engineering and Electronics, Brownlow Hill, Liverpool, L69 3GJ, England.
- Tokai University, Orido 3-20-1, Shimizu, Shizuoka 424, Japan. Internet: http://mackato.os.tokai.jp/katolabe.html
- Universita di Ancona, Dipartimento Elettronica e Automatica, via Brecce Bianche, 60131 Ancona, Italy.
- University of California - Riverside, College of Engineering, Riverside, CA 92521.
- University of Connecticut at Avery Point, U.S.
- University of Durham
- University of Genova, Via Opera Pia 11A, I - 16145 Genova, Italy.
- University of Hannover, Institut fur Fertigungstechnik und Spanende Werkzeugmaschinen, ScholBwender Str. 5, D-30159 Hannover, Germany
- University of Hawaii at Manoa, Department of Mechanical Engineering, Honolulu, HI 96822.

- University of Maine, Computer Science Department, Orono, ME 04468.
- University of Maryland, Institute for systems Research and Department of Electrical Engineering, College Park, MD 20742.
- University of Massachusetts Dartmouth, 285 Old Westport Road, North Dartmouth, MA 02747-2300. Phone the Graduate Program Director at 508-999-8434. Internet at: http://www.ece.umassd.edu/ece/welcom2.htm
- University of Miami, Coral Gables, FL 33124.
- University of Michigan, Ann Arbor, MI 48109
- University of New Hampshire, Department of computer Science, Durham, NH 03824.
- University of New Mexico, ME Dept., Albuquerque, NM 87131.
- University of Newcastle upon Tyne, Department of Marine Technology, Newcastle upon Tyne, U.K.
- University of North Carolina, U.S.
- University of Pennsylvania, U.S.
- University of Rhode Island, Narragansett, RI 02882
- University of Rome (Italy)
- University of Southampton, Highfield, Southampton, SO17 1BJ, England.
- University of Southwestern Louisiana, Robotics and Automation Laboratory, Lafayette, LA 70504
- University of Sydney, Ocean Technology Group, Dr. Ian S.F. Jones
- University of Texas Pan American, Edinburg, TC 78539.
- University of Tokyo, Institute of Industrial Science, Tokyo, Japan. <http://underwater.iis.u-tokyo.ac.jp>
- University of Victoria, Department of Mechanical Engineering, P.O. Box 3055, Victoria, B.C., Canada. V8W 3P6.

- University of Virginia, U.S.
- University of Washington, Applied Physics Lab, Seattle, WA, U.S.
- University of Wisconsin, Center for the Mathematical Sciences, Madison, WI 53715.
- University of South Florida, Department of Marine Science, St. Petersburg, FL 33701.
- University of San Paulo, Brazil.
- Woods Hole Oceanographic Institution, Woods Hope, MA 02543. www.whoi.edu

Additionally:

Florida Atlantic University offers an extensive program in ocean engineering including unmanned undersea vehicles. Contact the Department of Ocean Engineering, FAU, Boca Raton, FL 33431. http://www.oe.fau.edu/AMS/auv.html

Florida Institute of Technology has an ocean engineering program, including ROVs. Contact Florida Institute of Technology, Division of Marine and Environmental Systems, 150 West University Blvd, Melbourne, FL 32901-6975. Phone 407-768-8000, x8096.

Scripps Institution of Oceanography – The Ridge Inter-disciplinary Global Experiments (RIDGE), which plans to use unmanned vehicles to explore undersea for months or years (should be an interesting project).

Texas A&M - Galveston: TAMUG is considered A&M's "Window to the Sea." The six majors available at the Galveston campus include marine biology and fisheries, maritime administration, marine transportation, marine engineering technology, marine sciences and maritime systems engineering - all of which emphasize the maritime and marine industries. Contact the MTS student chapter for more information.

Woods Hole Oceanographic Institution - Jason Project - In an attempt to encourage more youngsters to study the ocean, each year the Jason Project allows hundreds of thousands of students the opportunity to participate in an interactive computer adventure. A past highlight of the expeditions has been the real time control of the Jason ROV by participating students via satellite links. The Jason project was founded by Dr. Robert Ballard of Woods Hole Oceanographic Institution. Additional information can be obtained from WHOI or at the web site: http://seawifs.gsfc.nasa.gov/JASON.html.

PROFESSIONAL SOCIETIES

Marine Technology Society, 1828 L. Street, N.W., 9th Floor, Washington, D.C. 20036

The Marine Technology Society has student chapters at:

- California State University
- Florida Atlantic University
- Florida Institute of Technology
- Orange Coast College
- Texas A&M University
- Texas A&M University – Galveston
- University of Miami (Florida)
- U.S. Merchant Marine Academy
- U.S. Navy Academy
- University of Rhode Island

MTS also has the following relevant committees:

- ROV Committee
- AUV Committee
- Underwater Imaging
- Manned Submersibles
- Remote Sensing
- Diving
- Cables and Connectors

The Marine Technology Society, Remotely Operated Vehicle Committee, administers an annual scholarship award. For information, visit the committee web page at www.rov.org.

Contact the Marine Technology Society for points of contact for the above chapters and committees.

The Society for Underwater Technology (SUT), U.K., oversees a program to attract the brightest and best students towards careers in marine science and technology. The program is primarily supported by offshore oil companies. For additional information, contact the SUT at 76 Mark Lane, London, U.K., EC3R 7JN. Tel: (0171) 481-750. Fax: (0171) 481-4001

The Association of Diving Contractors (ADC) provides an annual award of $50,000, to perpetuate the diving profession by stimulating the entry of top candidates into the underwater industry. Interested parties can submit a request for information to the Association of Diving Contractors, Scholarship Committee, 2611 FM 1960 West, Suite F-204, Houston, TX 77068.

The Society of Naval Architects and Marine Engineers, 601 Pavonia Avenue, Jersey City, NJ 07306. Phone 201-798-4800.

Junior Engineering Technical Society (JETS), for high school level students, 1420 King Street, Suite 405, Alexandria, VA 22314-2715

National Society of Professional Engineers (NSPE), for scholarship information, 1420 King Street, Alexandria, VA 22314-2715

Institute of Electrical and Electronic Engineers, Oceanic Engineering Society, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331. 908-981-0060.

American Society of Mechanical Engineers.

U.S. GOVERNMENT

The following provides potential of financial and/or equipment support.

NOAA's National Undersea Research Center

The National Oceanic and Atmospheric Administration (NOAA) is responsible for the establishment of programs for the assessment, protection, development and utilization of U.S. underwater resources. In addressing this mandate, NOAA's Office of Undersea Research initiated the National Undersea Research Program (NURP), which currently consists of six regional Centers for support of in situ research and technological development. In addition, to the West Coast Center, NURP centers serve the northeastern U.S. and the Great Lakes, Middle Atlantic Bight, Southeastern U.S., Caribbean and the Hawaiian Archipelago. The West Coast National Undersea Research Center was established in 1990 at the University of Alaska Fairbanks (UAF). The center will support highly-rated, peer-reviewed proposals to conduct in situ research in the West Coast region, including Alaska, and Polar regions. The center provides funds for salary and project support, which may include the use of manned research submersibles or ROVs. The Center will arrange for use of a NURP-owned ROV or for lease of an appropriate ROV. Depth capability and instrumentation can be matched to the project. Funds for lease of a support vessel also may be provided. Potential ROVs available in 1999 include *MEDEA-JASON* (WHOI), *VENTANA* (MBARI), *ROPOS* (Institute of Ocean Sciences in British Columbia, Canada), *ATV* (U.S. Navy) and *SUPER SCORPIO* (U.S. Navy). For information on submission of proposals contact: West Coast National Undersea Research Center, School of Fisheries and Ocean Sciences, P.O. Box 757220, 208 O'Neill, University of Alaska Fairbanks, Fairbanks, AK 99775-7220, phone: 907-474-5870, fax: 907-474-5804, email: westnurc@imc.alaska.edu, website: http://www.wcnurc.alaska.edu:8000/.

Sea Grant

The mission of the National Oceanic & Atmospheric Administration's National Sea Grant College Program is to conduct research, education, and outreach so as to promote the use of coastal and marine resources consistent with a sustainable economy and environment. Sea Grant is a network of 29 universities and institutions in U.S. coastal and Great Lake states and Puerto Rico. Through federal and matching funding, it supports research, education, and outreach - primarily at the state and local level. This covers the range from pre-college (K-12), college and informal education projects. Teachers receive hands-on training through "Operation Pathfinder" although, the primary investment is through the support of graduate students. Contact: www.mit.edu/seagrant/edu/

Other

Augmentation Awards for Science and Engineering Research Training (AASERT) - The Department of Defense has provided up to 353 awards to 112 academic institutions in the past to support graduate student training in science and engineering fields important to national defense. Past awards have provided three years of support to 401 students - averaging $135,000. The AASERT program is administered by the director of Defense Research and Education.

Defense University Research Instrumentation Program (DURIP) - The DURIP enables Department of Defense supported university researchers to purchase scientific equipment that costs more than $50,000. Recent awards included 273 to 105 academic institutions in the range of $47,000 to $700,000. Research is required in selected areas of importance to the DoD. Contact the Director of Defense Research & Engineering.

National Oceanographic Partnership Grants – The National Ocean partnership Program (NOPP) was established by Congress in 1996 to provide a formal mechanism to coordinate sharing of resources, intellectual talent, and facilities in the ocean sciences and education. Approximately half the recipients are from academic institutions, one-third are from industry and private institutions, and the remainder from federal or other government activities. The Senate Appropriations Committee has included as much as $28.8 million for the Partnership Program in the past. Contact: 703-696-5032/3; Internet: http://www.onr.navy.mil/sci_tech/ocean.

DEPSCoR Program - The Department of Defense awarded up to $18.36 million in the past to 24 academic institutions in 19 states to perform research in science and engineering fields important to national defense. The Office of Naval Research runs the Defense Experimental Program to Stimulate Competitive Research (DEPSCoR).

Multidisciplinary University Research Initiative (MURI) - This DoD program addresses topic areas that represent exceptional opportunities for future DoD applications. Over $19 million in awards has been provided to 22 academic institutions in the past by the ONR sponsored program.

MUSEUMS AND MISCELLANEOUS

For information on undersea vehicles and diving, visit the following:

Museum of Man in the Sea, 17314 Back Beach Road (West Hwy. 98), Panama City Beach, FL 32413. Phone 904-235-4101

The Navy Museum, Washington Naval Shipyard, 9th and M Streets S.E., Washington, D.C. 20374-0571. US 202-433-4882

Naval Undersea Museum, Keyport, Washington, US, Phone 360-396-4148
Web page: <http://num.kpt.nuwc.navy.mil/>

Scott Carpenter Man in the Sea Program - Although this program includes manned submarines, undersea habitats, diving bells and scuba diving, the addition of ROVs may not be far behind. The program provides the opportunity for participants to live, study and explore under water. The Man in the Sea program is run by the non-profit Marine Resources Development foundation in Key Largo, Florida.

APPENDIX E. TRAINING ORGANIZATIONS

The following companies or training centers have been listed in various publications as providing training in the area of ROVs, diving and/or offshore practices.

Cable and Wireless Global Marine

College of Oceaneering
Wilmington, CA, USA
310-834-2501

Commercial Diver Training Center

Divers Academy of the Eastern
Seaboard, Inc.
2500 Broadway
Camden, NJ 08104
Tel: 609-966-1871
1-800-238-DIVE
Fax: 609-541-4355
www.diveweb.com/diversacademy

Divers Institute of Technology
P.O. Box 70667
Seattle, WA 98107
Tel: 206-783-5542
Fax: 206-783-2658

Hydrovision USA/Subsea Services
222 Meigs Road #18
Santa Barbara, CA 93109
Tel: 805-899-3699
Fax: 805-899-3699

Fort Bovisand Underwater Centre
Plymouth, Devon, PL9 0AB England
Tel: 01752408021
Fax: 01752481952

Idaho Institute of Robotics

Interdive Services
22 Leyford Close Wembury
Plymouth, Devon, PL9 0HX
Tel: 01752863235
Fax: 01752481952

Louisiana Technical College

Oceaneering International, Inc.
1191 FM 529
Houston, TX USA 77084

Professional Divers Institute, Inc.
P.O. Box 546
Long Beach, MS 39560
Tel: 228-868-6900
Fax: 228-868-6996
www.diveweb.com/pdi

Rumic Ltd.
83 Abbey Rd. Barro-in-Furness
Cumbria LA14 5ES England
Tel: 01229823956
Fax: 01229836917

Santa Barbara City College
Marine Technology Program
721 Cliff Drive
Santa Barbara, CA USA
Tel: 805-965-0581
Fax: 805-963-7222

Scottish National Test Centre
Univ. Of Paisley, High Street
Paisley, PA1 2BE, Scotland
Tel: 01418483666
Fax: 01418483663

SubServ Management &
Training Consultants
Windermere, Cumbria, UK.
Tel/Fax: 015394 4402

Texas A&M Center for Marine Training and Safety
ROV Pilot and Technician Training Institute.
Galveston, TX USA

The Ocean Corporation
Houston, TX USA

The Underwater Center
Fort William, Inverness-shire
PH33 6LZ Scotland
Tel: 44 1397 703786
Fax: ...704969

The Underwater Center
Tasmania Pty Ltd.
Inspection Head Wharf
P.O. Box 342
Beauty Point, Tasmania 7270
Tel: 61 3 6383 4844
Fax: 4850

Wray Castle Ltd.
Ambleside
Cumbria, LA22 0JB England
Tel: 01539432320
Fax: 0139432845

APPENDIX F. INTERNATIONAL COLOR TV FORMATS

Country	Color Standard
Albania	PAL
Antilles Netherlands	NTSC
Argentina	PAL
Australia	PAL
Austria	PAL
Azores (Portugal)	PAL
Bahamas	NTSC
Bahrain	PAL
Bosnia and Herzegovina	PAL
Belgium	PAL
Bermuda	NTSC
Brazil	PAL
Bulgaria	SECAM
Canada	NTSC
Chile	NTSC
China	PAL
Columbia	NTSC
Crotia	PAL
Czech Republic	SECAM/PAL
Denmark	PAL
Egypt	SECAM
Finland	PAL
France	SECAM
Germany	PAL
Germany (previously East)	SECAM/PAL
Greece	SECAM
Hong Kong	PAL
Hungary	PAL
Iceland	PAL
India	PAL
Indonesia	PAL
Iran	SECAM
Ireland	PAL
Israel	PAL
Italy	PAL
Jamaica	SECAM
Japan	NTSC
Korea – South	NTSC
Korea – North	SECAM
Malaysia	PAL
Mexico	NTSC

Morocco	SECAM
Netherlands	PAL
New Zealand	PAL
Norway	PAL
Paraguay	PAL
Peru	NTSC
Philippines	NTSC
Poland	PAL
Portugal	PAL
Russia	SECAM
(includes former USSR countries)	
Romania	PAL
Saudi Arabia	SECAM
Serbia	PAL
Slovania	PAL
Slovakia	SECAM/PAL
Singapore	PAL
South Africa	PAL
Spain	PAL
Switzerland	PAL
Taiwan	NTSC
Thailand	PAL
Turkey	PAL
United Arab Emirates	PAL
United Kingdom	PAL
United States	NTSC
Uraguay	PAL
Venezuela	NTSC

APPENDIX G. ENVIRONMENTAL DATA

Appendix G, Environmental Data, contains the following sections:

- Sea State Chart
- Arctic Environmental Conditions

SEA STATE CHART

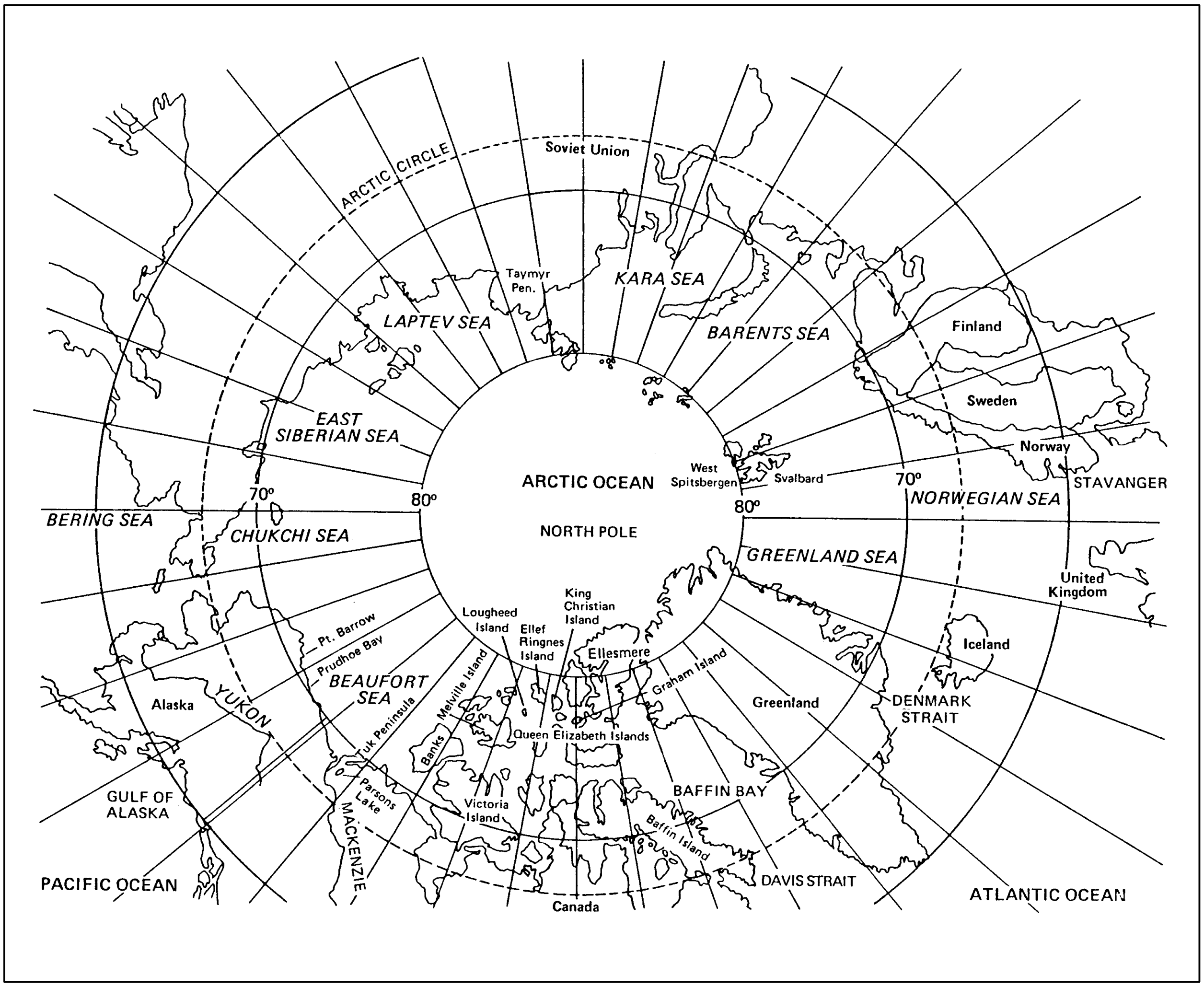
Wind and Sea Scale For Fully Arisen Sea

Sea-General		Wind			Sea	
Sea State	**Description**	**(Beaufort) Wind Force**	**Description**	**Range (Knots)**	**Wave Height Feet Average**	**Significant Range of Periods (Seconds)**
0	Sea like a mirror.	0	Calm		0	—
	Ripples with the appearance of scales are formed, but without foam crests.	1	Light Airs	1-3	0.05	up to 1.2 sec.
	Small wavelets, still short but more pronounced. Crests have a glassy appearance and do not break.	2	Light Breeze	4-6	0.18	0.4-2.8
1	Large wavelets. Crests begin to break. Foam of glassy appearance. Perhaps scattered white caps.	3	Gentle Breeze	7-10	0.6 0.88	0.8-5.0 1.0-6.0
2 3	Small waves becoming longer; fairly frequent white caps.	4	Moderate Breeze	11-16	1.4 1.8 2.0 2.9	1.0-7.0 1.4-7.6 1.5-7.8 2.0-8.8
4	Moderate waves, taking a more pronounced long form; many white caps are formed. (Chance for some spray.)	5	Fresh Breeze	17-21	3.8 4.3 5.0	2.5-10.0 2.8-10.6 3.0-11.0
5 6	Large waves begin to form; the white foam crests are more extensive everywhere. (Probably some spray.)	6	Strong Breeze	22-27	6.4 7.9 8.2 9.6	3.4-12.2 3.7-13.5 3.8-13.6 4.0-14.5
	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of wind. (Spindrift begins to be seen.)	7	Moderate Gale	28-33	11 14 14 16	4.5-15.5 4.7-16.7 4.8-17.0 5.0-17.0
7 8	Moderately high waves of greater length; edges of crests begin to break into the spindrift. The foam is blown in well-marked streaks along the direction of the wind. Spray affects visibility.	8	Fresh Gale	34-40	19 21 23 25 28	5.5-18.5 5.8-19.7 6.0-20.5 6.2-20.8 6.5-21.8
	High waves. Dense streaks of foam along the direction of the wind. Sea begins to "roll". Spray may affect visibility.	9	Strong Gale	41-47	31 36 40	7-23 7-24.2 7-25
9	Very high waves with long overhanging crests. The resulting foam, in great patches, is blown in dense white streaks along the direction of the wind. On the whole, the surface of the sea takes a white appearance. The rolling of the sea becomes heavy and shock-like. Visibility affected.	10	Whole Gale	48-55	44 49 52 54 59	7.5-26 7.5-27 8-28.2 8-28.5 8-29.5
	Exceptionally high waves (small and medium-sized ships might be for a time lost to view behind waves.) The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the waves are blown into froth. Visibility affected.	11	Storm	56-63	64 73	8.5-31 10-32
	Air filled with foam and spray. Sea completely white with driving spray; visibility very seriously affected.	12	Hurricane	64-71	>80	10-(35)

ARCTIC ENVIRONMENTAL CONDITIONS

There is little doubt that the oil and gas industry views the Arctic regions as a major area of activity in the very near future. ROVs have a potentially significant role in the support of these forthcoming activities and the subsequent development and production stages.

In these regions the existence of sea ice and severe cold temperatures pose significant challenges to the design, operation, and deployment of ROVs. For the purpose of this discussion the Arctic and sub-Arctic will include all areas where significant sea ice cover may occur. This area is shown in the following figure, but not specifically limited to the areas shown. Specifically, Arctic-like environmental conditions can and do exist on lakes and rivers as far south as the central United States in the winter. This appendix describes a variety of Arctic conditions, which will be factors that an ROV operator must cope with to work successfully under Arctic and Arctic-like conditions.



Arctic Regions

Meteorological Conditions

The cold sub-Arctic and intensely cold Arctic significantly hamper human activity and promote major problems in the operation and maintenance of equipment and machinery. Cold temperatures preclude the use of many conventional pieces of equipment, materials and procedures. The cold temperatures in conjunction with winds and precipitation additionally compound operational difficulties

Air Temperature

Persistent very cold temperatures in the Arctic and sub-Arctic set these areas apart from the rest of the world. Representative air temperatures for the Beaufort and Bering Sea, and North Atlantic are listed in the table below. In the case of offshore, heat input also comes from long-wave radiation emanating from the surface. As a result, air temperatures offshore and along the coast tend to be somewhat milder and uniform than at inland or interior locations. Severe limitations are put on equipment and materials in many Arctic and sub-Arctic areas due to the occurrence of -4^{o}F (-20^{o}C) and below temperatures. Basically things that work in warm climates typically either don't work or break in the Arctic. Equipment and parts redundancy is essential as a result of this environment.

Mean Monthly Air Temperatures for Various

Arctic and Subarctic Locations - Centegrade

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Barrow, Alaska	-26	-28	-26	-18	-7	+1	+4	+3	-1	-9	-18	-25	-13
Churchill, Canada	-28	-27	-21	-10	-1	+6	+12	+11	+5	-3	-14	-24	-8
Godhaven, Greenland	-12	-14	-13	-7	0	+5	+8	+7	+3	-2	-6	-9	-3
Nome, Alaska	-14	-15	-13	-7	+2	+8	+10	+9	+6	-2	-9	-15	-4
St. Paul, Alaska	-3	-5	-5	-2	+2	+5	+8	+9	+7	+3	+1	-2	+1
Thule, Greenland	-25	-25	-27	-17	-5	+3	+6	+5	-2	-10	-18	-23	-11

Mean Monthly Air Temperatures

Precipitation

The Arctic area is a very dry climate averaging about 6 in (15.2 cm) of precipitation along the Alaskan coast per year. About 1/3 of this falls as rain during the short summer season. Precipitation amounts for the Bering Sea range from 16.5 in (42 cm) at Nome to 26 in (66 cm) near Saint Paul Island. Snow fall amounts on a yearly basis amount to 30, 55 and 60 in (76, 140 and 152 cm) at Point Barrow, Nome, and Saint Paul Island, respectively. The high Arctic, for example Resolute, receives approximately 5 in (12.7 cm) of precipitation per year. On the east coast, total precipitation ranges from 6 to 50 in (15.2 to 127 cm) along the coast from St. John, New Brunswick northward into Baffin Bay to Thule, Greenland.

Significant snow fall in the Arctic in combination with strong winds results in drifting and blowing snow, giving way to the buildup of snow drifts, and causing reduced visibility, which hampers transportation.

Winds

Wind conditions along the Alaska north coast are relatively light in comparison to the sub-Arctic areas in the Bering Sea and North Atlantic. In the Prudhoe Bay area, for example, wind speeds exceed 30 knots (55.6 km/hr) only 3 percent of the time. Annually directional winds predominate from east to northeast 50 percent of the time and west to southwest 20 percent of the time.

In the sub-Arctic areas and into the southern Bering Sea and North Atlantic wind speeds are strong and persistent. In the St. George Basin and Hibernia area, for example, wind speeds exceed 30 knots (55.6 km/hr) approximately 9 percent and 12 percent of the time, respectively. As a result, wave conditions developed in the winter season in these areas can be extreme as discussed later in Oceanographic Conditions.

Another major operational difficulty associated with increased winds in the Arctic areas is the wind chill effect. This effect severely affects man's productivity and efficiency when working outside in the environment. Precautions should be made to provide shelter when working in exposed locations.

Visibility

Reduction of visibility can be caused by precipitation, fog, or blowing snow. The occurrence of each parameter is usually more likely during a particular season. Each regional area is also more susceptible to one or more causes of reduced visibility.

In the Arctic along the Beaufort coast and in the Arctic islands, blowing snow occasionally reduces surface visibility during the winter months. Blowing snow generally remains in a low layer along the ground. This often restricts ground transportation, and, to a point, air transportation. Although ground visibility is restricted, it is often clear with unlimited visibility above the ground layer.

Two types of fog conditions limit visibility in the Arctic. The first and most important for offshore activity is advection fog, which is primarily caused by a significant temperature differential between the water and the air. During periods of reduced ice concentrations fog conditions often develop near the open water areas. The extent and severity of the fog condition is a function of the temperature differential and amount of ice cover. During breakup, through freeze-up in the Beaufort Sea, fog conditions significantly hamper both helicopter and boat operations.

The second type of fog condition is unique to the Arctic or where temperatures regularly drop below -13^{o}F (-25^{o}C). This is known as ice fog and is generated from human activity. A byproduct of human activity is water; from engines and motors, or combustion for power generation, transportation, etc. The injection of this moisture into very cold air creates local fog conditions, which are often quite dense. Typically this occurs from January through March.

In the Bering Sea and North Atlantic, the primary cause for reduced visibility is fog. Warm air flowing over the cold water, primarily during spring, significantly hampers offshore operations. Off Newfoundland, for example, this also occurs when icebergs are moving south into the area, creating a hazardous condition.

Oceanographic Conditions

In the Arctic and sub-Arctic, or in the case for this discussion, any area which experiences sea ice and icebergs, oceanographic conditions are wide ranging.

Wave conditions during open water season in some of the sub-Arctic areas approach some of the most severe in the world, such as in the Grand Banks area and the southern Bering Sea. Ice coverage and concentration significantly affect sea state conditions as open water fetches become limited and ice cover damps out wave propagation.

Limited data and information exists on ocean currents in the Arctic simply because of man's low level of interest in the past. However, significant amounts of data are now being collected to support oil company exploration efforts in these areas, but most of it is not in the public domain.

Waves

In the Beaufort Sea, wave generation is limited to the summer open water season, which generally lasts two to three months along the Alaskan coast and three to four months along the Canadian coast. The extent of wave generation is again limited by ice coverage. In the Beaufort Sea, the location of the ice edge from year to year is highly variable. The ice edge may be located only 8 nm (14.8 km) from shore to as much as 135 nm (250 km). As a result, wave generation from similar storms occurring in different years can be highly variable.

In the Alaskan Beaufort Sea for example, waves can be expected to exceed 5 ft (1.5 m) only abut 10 percent of the time while generally being of short period. The occurrence of higher wave heights, longer wave periods, and the potential for extreme conditions increase the further south one goes into the sub-Arctic in the Bearing Sea or North Atlantic. In these areas, conditions approach very severe limits, exceeding 10-ft (3-m) wave heights 30 percent of the time with longer periods.

Design wave heights approach 40 ft (12 m) in the Alaskan Beaufort Sea and 90 to 100 ft (27 to 30 m) off Newfoundland and the southern Bering Sea.

Currents and Turbidity

Only limited data exists regarding currents in the Arctic and sub-Arctic. In the Beaufort Sea, wind driven currents and river outflow dominate the current regime during the short open water season. Current data below ice is extremely limited. Some data was collected from the AIDJEX experiment below ice but was not in the present area of interest: the Beaufort Sea. The dominant mechanism producing currents during ice covered periods appears to be tides. Sea water density variability due to melting ice as well as river outflow can also create complex current regimes.

In the sub-Arctic areas (the Bering Sea and North Atlantic) anticipated currents are not unlike other open ocean areas during the respective seasons. During the ice covered periods, reduced currents are anticipated due to reduced wind driven current. However, density or thermally generated currents are expected to create complex current regimes.

Little or no information is available on local turbidity, however, in the Beaufort Sea, soft soil conditions of fine silts and persistent long-shore transport will likely cause significant reduced visibilities in shallower waters. Typical conditions observed during Canadian operations have averaged 0 to 10 ft (0 to 3 m) visibility from June to November.

Tides

Astronomical and storm tides are fairly well understood and documented in the Arctic and sub-Arctic areas. Astronomical tides are less than 3 ft (0.9 m) in the Beaufort Sea. In the Bering Sea, tide ranges vary from 3 ft (0.9 m) in the central Bering to 13 ft (4 m) in the eastern end of the North Aleutian Shelf sale area. Astronomical tides range from 34.5 to 39 ft (10.5 to 11.9 m) inside some inlets and embayments along the Labrador coast to 5 to 10 ft (1.5 to 3 m) off Newfoundland .

Tides associated with wind conditions are more important along the Beaufort coast, where setup may exceed 3 ft (0.9 m) along the coast on any given year.

In the Bering Sea, Norton Sound because of its geometry, will occasionally experience tides from 5 to 10 ft (1.5 to 3 m) in any given year. Current exploration activity in the remainder of the Bering Sea is in relatively deep water where only minor storm tidal fluctuations are experienced. This is also the case off Newfoundland.

Temperature and Salinity

Water temperatures in the Beaufort Sea generally range from 29.3^{o}F (-1.5^{o}C) or very near freezing, from the surface to a depth of 98 ft (30 m). From 98 ft (30 m) and below, temperatures in this subsurface layer remain fairly constant at about 30.2^{o}F (-1.0^{o}C). The surface layer in summer often only penetrates 16 to 32 ft (4.9 to 9.8 m) and may reach as high as 42.8^{o}F (6^{o}C). Local conditions may vary due to melt water, river discharge, and wind mixing.

Bering Sea temperatures are wide ranging, because locally grown ice occurs in the Norton Sound into the central Bering Sea. The Navarin Basin area water temperatures just reach 29.3^{o}F (-1.5^{o}C) in the coldest month with sea surface temperatures approaching 46.4^{o}F (8.0^{o}C) in August. Sea temperatures off the east coast of Canada to the Hibernia area are similar to the Bering Sea.

Beaufort Sea salinity, in the upper layer, is generally 25 ppt (parts per thousand) becoming 35 ppt below 98 ft (30 m). The surface layer is also variable due to melt water and river discharge. In addition, directly below the ice cover, local salinities approach 35 to 45 ppt due to brine drainage. In the Bering Sea, salinities are typically 25 to 30 ppt.

In the North Atlantic off Labrador and Newfoundland, salinities range from 30 to 35 ppt regionally. The Labrador current, which flows through the area, is from 32 to 34 ppt.

Ice Conditions

The presence of sea ice and glacial ice in the Arctic and sub-Arctic areas requires innovative methods for oil and gas exploration and production. The presence of ice also requires new approaches in the ROV field. Ocean access will be either partially or completely blocked by the presence of sea ice. This, in some respects, may be an advantage as the ice cover either damps out or eliminates ocean waves and its associated problems relative to the operation of ROVs. If the sea ice cover is moving, however, this again can create unique problems.

Ice can be used as a fairly stable platform for the deployment of ROVs. This, of course, depends on its thickness, strength, and potential for movement. Ice, as a material, possesses unique characteristics both in its mineral properties as well as the unique geometric configurations that it assumes. Ice coverage also is a significant variable from location-to-location, season-to-season, and year-to-year.

Ice Properties

The specific properties that ice possesses is determined by its age, strength, origin, and growth history. From the evaluation of a few simple parameters, in particular salinity and temperature, various ice strengths may be determined.

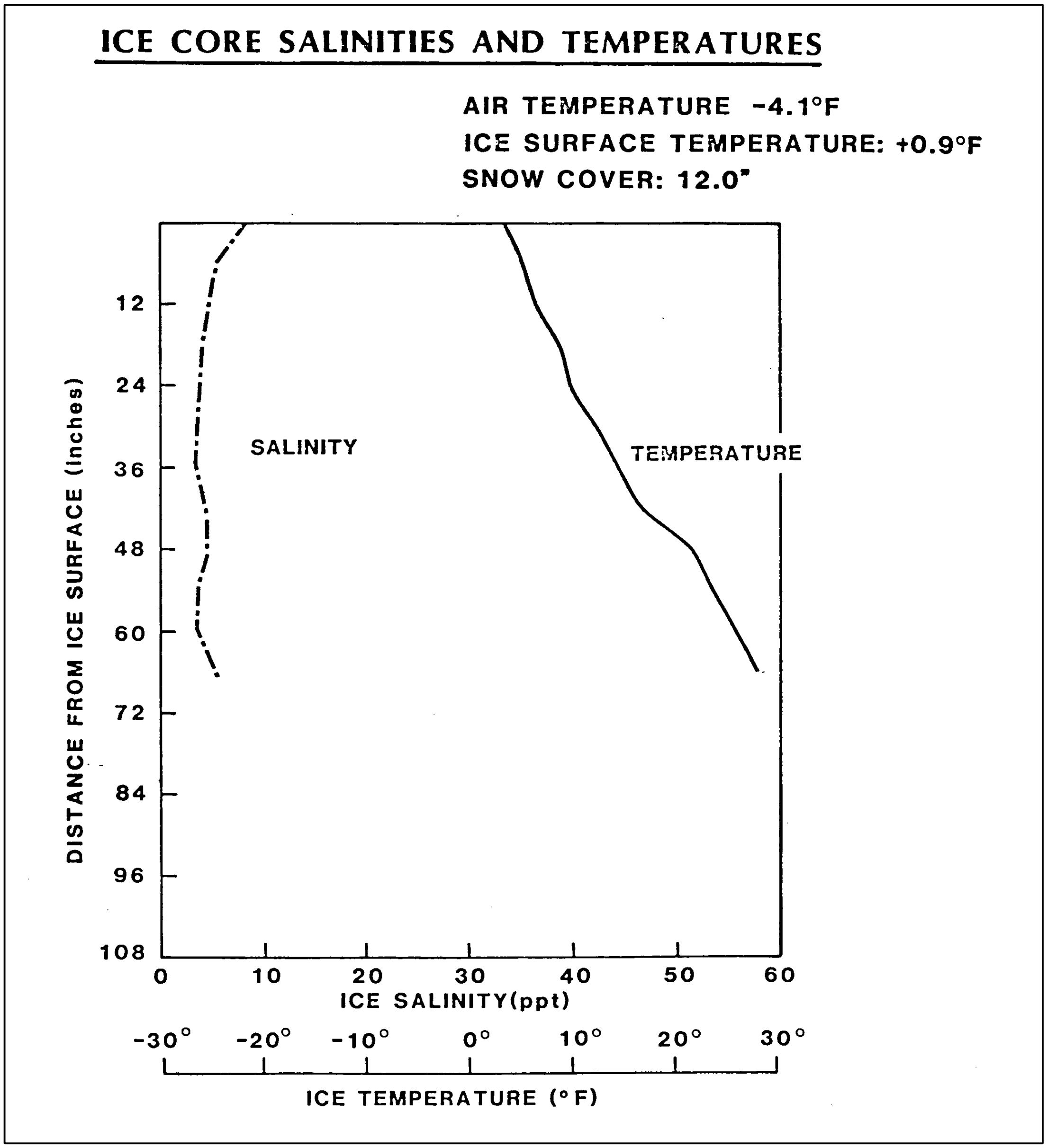
Ice Growth and Decay

Sea ice growth is obviously a function of air temperature, and as a result, numerous formulas have been developed to calculate the growth as well as decay of sea ice. Typical sea water freezes at 29^{o}F (-1.7^{o}C). The colder it is and the longer it stays that cold, the faster and thicker the ice will grow. Typical sea ice thickness experienced at the onset of spring can range up to 6.5 and 11.5 ft (2 and 3.5 m) in the Arctic Ocean and the Canadian high Arctic, respectively. Thicknesses of about 1.5 ft (0.5 m) are typical along the Canadian east coast and central Bering Sea.

Ice decay may occur due to warm air temperatures, wave action, or the advection of the sea ice into warmer water. This is the case in the southern Bering Sea and Grand Banks area.

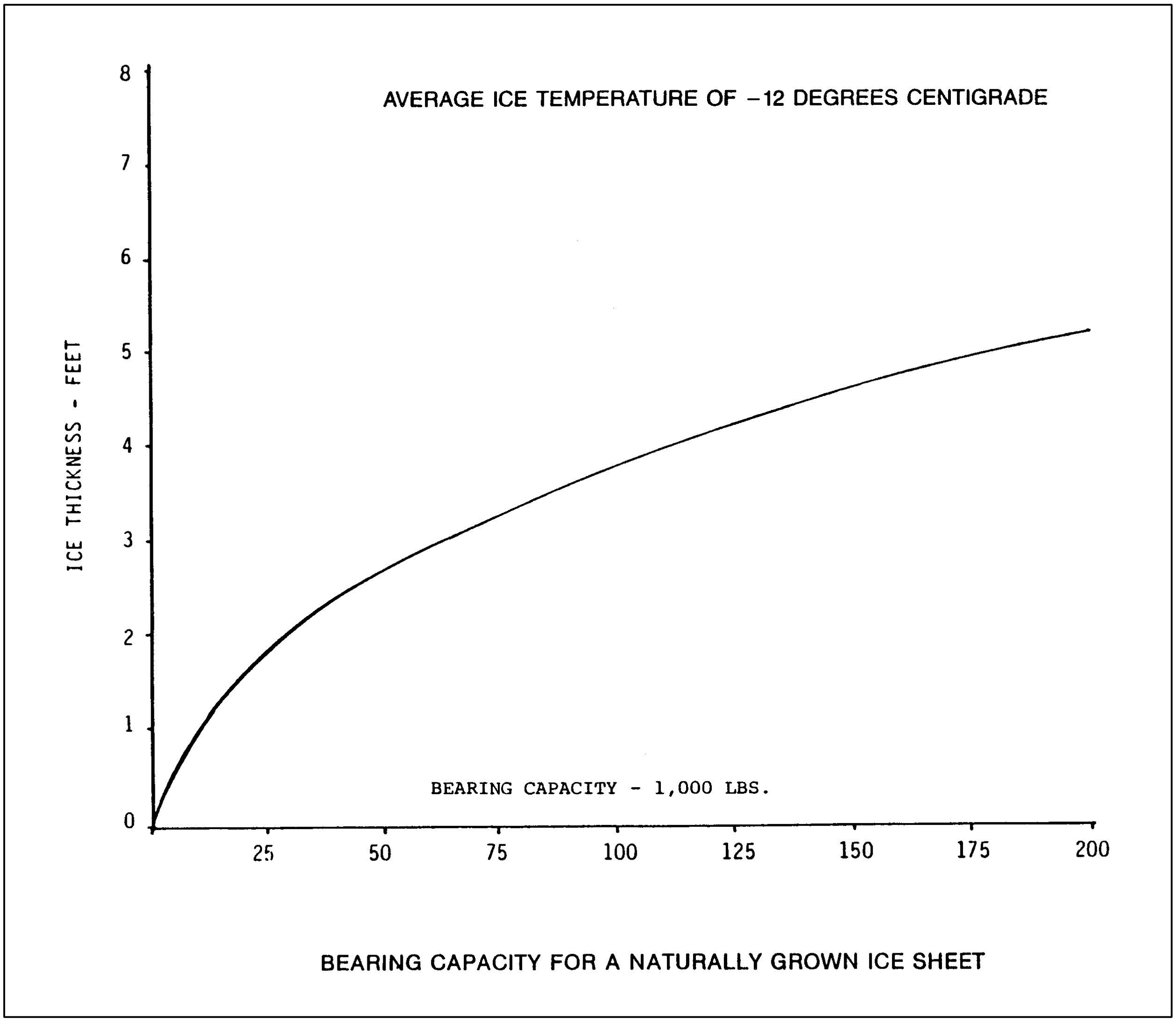
Temperature

Ice temperature greatly affects the strength of sea ice. Cold temperature penetration into the ice is often promoted by snow removal efforts when the ice is used as a platform or road. The warm water below 34.9°F (1.6°C) will warm the ice sheet when a snow cover is allowed to insulate the ice from the air temperatures. A typical ice temperature profile is shown in the figure below.



Salinity

Ice salinity also affects the strength of ice. First year ice at freezeup is fairly high in salt content. As the sheet begins to grow, the salt slowly drains out of the ice through brine drainage. As a result, the sheet gradually becomes stronger with time as the salt content slowly drops. Multi-year ice, ice island fragments and icebergs, while being formed in different ways, have little or no salt content. A typical first-year sea ice salinity profile is shown in the figure on the previous page.



Bearing capacity for a naturally grown ice sheet

Ice Strength and Bearing Capacity

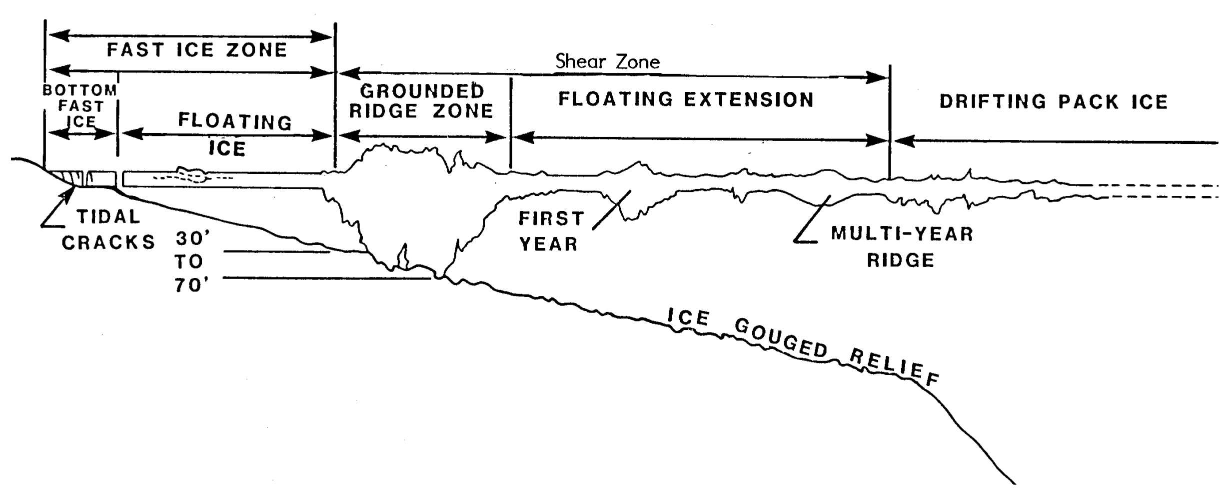
As discussed earlier, ice strength is primarily a function of ice temperature and salinity. It also is a function of loading rate, and ice crystal orientation. Therefore, it is difficult to give any specific numbers on ice strength. Typical values being used for design of Arctic structures and ships, for first year ice, range from 200 to 400 psi in crushing and 50 to 100 psi in flexure. This depends on the size of the loaded area. Multi-year ice and glacial ice (ice islands and icebergs) may be two to four times as strong as first year ice. Ice has been used as platforms and roads for offshore exploration. The ice is often artificially thickened to attain a thickness that will support the anticipated loads. Bearing capacity for a naturally grown first year ice sheet is shown in the figure on the previous page.

Ice Features

The existence of various types of ice features is a result of ice growth history and origin and movement.

Landfast

Landfast ice is typically referred to as ice that is attached to a shoreline and/or extends to various grounded ice features. The extent of the landfast ice zone is dependent upon shoreline geometry and offshore bathymetry. Where areas for potential ice movement is low, the landfast zone is generally large. If ice becomes grounded at shoal areas, this typically expands the landfast zone as ice movement potential has decreased shoreward of the grounded feature. The landfast zone becomes gradually larger throughout the season as features become grounded and the ice sheet becomes more stable (see the following figure).



Ice zonation

Pack Ice

Pack Ice is any area of sea ice that is not landfast. In the Arctic Ocean, the pack contains multi-year ice, which is ice that has survived one or more melt seasons. The pack is continually moving and, as a result of ice-ice interaction, constantly deforming (see previous figure).

Shear Zone

The shear zone, or transition zone, is where the landfast ice meets with the pack ice. This zone is usually heavily deformed and may be up to tens of miles wide depending on seasonal and annual changes. The zone typically grows gradually seaward throughout the season as features become grounded, promoting further deformation as the pack moves (see previous figure).

Ice Islands and Icebergs

These ice features are products of the glacial ice shelves and the ice cap, which calve off into the ocean. In the Arctic Ocean, these ice features are called ice islands and are typically 20 to 150 ft (6 to 46 m) thick. Often, early Arctic explorers would sight these features and confuse them with land. icebergs, which pose a problem to shipping and oil development off the east coast of Canada, generally form from the various glaciers on Greenland calving off into the North Atlantic. Typically these glaciers are from 300- to 1,000-ft (91- to 305-m) thick.

Shear and Pressure Ridges

Shear and pressure ridges are linear ice features composed of broken ice blocks created from ice pressure and movement. A pressure ridge is formed by buckling, bending, or local crushing of colliding ice floes with relative motion in a direction primarily perpendicular to their common boundary. Generally composed of stacked ice blocks, a pressure ridge tends to be a curvilinear feature with sloping sides.

A shear ridge on the other hand is formed by relative motion of two ice features in a direction primarily parallel to their common boundary. A shear ridge is composed of ground-up ice chips and pieces and is usually a straight line feature with a vertical face.

Rubble Fields (Rubble Piles)

A rubble field or pile is created by significant ice motion composed of broken ice pieces and blocks. They may be either floating or grounded and often have a characteristic elliptical shape.

Ice Gouges

Ice gouges are the result of ice features under motion that come in contact with the sea bottom. The ice feature may plow out an area before either entering deeper-water or grounding. Significant ice gouges occur in water depths to 150 ft (46 m) in the Arctic Ocean, or in the case of areas with icebergs, to water depths of some 1,500 ft (457 m). Typical gouges in the Arctic Ocean are almost 3 ft (0.9 m) deep. Extreme gouges caused by icebergs have been observed to 15 ft (4.6 m) deep.

Ice Seasons

Seasonality of the ice cover primarily affects transportation and oil and gas exploration efforts. The extent of ice cover often defines whether or not the area is considered "Arctic." "Season length" ranges from essentially zero days open water in the polar pack, to perhaps just 50 nm (93 km) north of the north slope, or to just a few days ice cover per year in the southern Bering Sea or off eastern Canada near Newfoundland.

As a result of these seasonality variations, logistics and operational schedules are dictated by the ice. The variation from year to year is also significant and creates further scheduling and planning problems.

Permafrost

In the Arctic Ocean, subsea permafrost may be found at the sea bottom surface in water depths up to 13 ft (4 m) but generally from 6.5 ft (2 m) where the ice grows to maximum thickness and becomes landfast and anchored to the bottom. Spotty areas of surface permafrost may be found where grounded ice features may occur. Typically, permafrost may be found at 33 to 50 ft (10 to 15 m) below sea bottom near the coastline and existing islands. The top of the permafrost may be as much as 656 ft (200 m) below the sea bottom. Additionally, it is not a uniform distribution in thickness, elevation, or depth.

The significance of the subsea permafrost layer is such that subsea pipelines must be designed to account for the permafrost along the pipeline route. In the future, pipeline inspections will be necessary to evaluate the pipeline performance from ice gouging and potential thaw settlement.

APPENDIX H. UNDERWATER ACOUSTICS REFERENCES

For those of you who desire a greater understanding of the area of underwater acoustics, the following sources of additional information are available:

Training sessions

Pennsylvania State University. Penn State runs some very good introduction to acoustics (sonar) courses as summer classes.

Applied Technology Institute. A commercial training organization aimed towards the defense industry. Good basic acoustic courses.

Books, Papers

Urick, R. J., *Principles of Underwater Sound*, 3rd ed., McGraw-Hill Book Co. (Should be on most book shelves)

Brekhovskikh, Y. L., *Fundamentals of Ocean Acoustics*, Spinger-Verlag, Berlin. (Sounds like a mouthful, but a good all round text)

Kinsler, K.E., Frey, A.R., *Fundamentals of Acoustics,* 3rd ed., New York: John Wiley and Sons (A little heavy reading)

Burdic, W.S., *Underwater Acoustic System Analysis*, Prentice Hall, Inc. (Heavy going also)

Milne, P.H., *Underwater Engineering Surveys*, Gulf Publishing Co. (Dated [1979] but good background)

Milne, P.H., Underwater Acoustic Positioning Systems, Gulf Publishing Co. (Also dated [1983] but solid basics)

Bomford, G., *Geodesy*, Clarendon press, Oxford. (The Geodesy bible)

Kelland, N.C., Accurate Acoustic Position Monitoring of Deepwater Geophysical Towfish, OTC, 1988

Kelland, N. C., Forster, L.D., Precise Acoustic Positioning of Wellheads in Deepwater, MTS 1992

Pike T.T, Comparison of Speed of sound in water algorithms, Hydrographic Society, 1994

Manufacturers and survey companies

- Software

Blue Marble Geographic has a very good geodetic conversion program that is very inexpensive and always worth having on your laptop to check other conversions offshore.

- Hardware/System Manufacturers

USBL manufacturers

ORE	LXT
	Trackpoint II
Nautronix	RS7, Hydrostar
	RS900, 910 Series
	ATSII
Kongsberg Simrad	HPR 400P
	HPR 410
	HiPAP
Sonardyne	USBL

SBL Manufacturers

MORS (Oceano)	
Nautronix (Honeywell)	RS5D
Sonardyne	SBL

LBL Manufacturers

Benthos	
Imetrix	
Nautronix (Honeywell)	906, 916
Kongsberg Simrad	408
Kongsberg Simrad	418

Edgetech (EG&G)	
MORS (Oceano)	
Sonatech	
Sonardyne	L/USBLPAN, Compatt etc.
Combined LBL/USBL	

Integrated Systems Manufacturers

Nautronix (Honeywell)
Kongsberg Simrad
Sonardyne

Compasses - Digicourse, Syntron, Arthur d. Little, KVH, many others

Gyro's - Sperry, Anschutz, S.G. Brown, Litton C. Plath, Tokyo Keiki, Robertson, many others

VRU's/Attitude - TSS, Datawell, Seatex, Trimble, Ashtead, Sercel, many others