PAPER

The Present and Future Capabilities of Deep ROVs

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ABSTRACT

The following paper will present an overview of Remotely Operated Vehicles (ROVs) and, in particular, their use in the deep ocean, which includes depths beyond 10,000 feet. Although the intent of the paper is to address tethered, free-flying vehicles, the categories of deep towed vehicles and autonomous underwater vehicles (AUVs) will also be included for completeness. And, to properly discuss the state-of-the-art in such deep ocean systems, their capabilities in the depths less than 10,000 ft will also be addressed. An attempt to project their uses in the early stages of the next millennium will also be made.

INTRODUCTION

It is appropriate that MTS publish its first Journal issue of the new Millennium on the topic of Deep Ocean Frontiers. What topic is better suited for this inaugural issue than to discuss the ocean realm and the tools that will help us understand it, especially when considering that the health of this vast unknown frontier will likely determine the future of mankind. The importance of using unmanned vehicles to gain knowledge of the ocean was underscored by a National Research Council study (NRC, 1996), which put forth many recommendations directed toward achieving that goal. This Journal issue is also timely, in that the MTS Committee on Remotely Operated Vehicles has just completed a two-and-a-half year effort to publish a book on CD-ROM titled *Operational Effectiveness of Unmanned Underwater Systems* (Wernli, 1999), which provides a detailed examination of ROVs, AUVs and other remote systems. This paper will draw heavily upon the recent work of the ROV committee, which will aid in presenting a current overview of the technology. The use of deep water ROVs offshore continues to increase, and will expand even further in the future. This paper will summarize those capabilities and provide a projection of where the technology being developed will lead us in the future.

HISTORICAL PERSPECTIVE

Whether one identifies the beginning of the ROV by the development of Dimitri Rebikoff's *POODLE* in 1953, the *PUV* (Programmed Underwater Vehicle) Luppis-Whitehead Automobile torpedo developed in Fiume (then in Austria) in 1864, or the first wire-controlled torpedo co-invented by Sims/Edison in 1891, it has to be agreed that ROVs have come a long way. They have matured from early, unreliable systems, to vehicles capable of probing the ocean's depths, down to the magic 20,000 foot (6,096 m) barrier and beyond.

Initially, the US Navy had the missions that required unmanned vehicles, and accordingly, provided the financial backing to break down some of the technological barriers. Ultimately, through technology developed in the Navy's R&D centers and through cooperation with industry, Navy financed vehicles broke the 6,096 m barrier in 1990—not once, but twice. The first tethered ROV to reach the depth was the *CURV III* vehicle. Operated by Eastport International (now Oceaneering Technologies Inc.) for the US Navy's Supervisor of Salvage, *CURV III* reached a depth of 6,128 m. Then, less than a week later, that long sought record was again broken by the Advanced Tethered Vehicle's record dive to 6,279 meters. The *ATV*, developed by the Space and Naval Warfare Systems Center, San Diego, was then transferred to SUBDEVRON5 (Submarine Development Squadron Five—formerly the Submarine Development Group) Unmanned Vehicle Detachment in San Diego where it is now operated by fleet personnel.

The celebration of the depth records achieved by the US was short lived, however, as 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 obliterated it, reaching the deepest point on Earth in the Mariana Trench—10,911.4 m—in 1995. A record that can be tied, but never exceeded (at least not without a shovel).

These previous records are a tribute to engineering design and human determination, but the ability to reach a given depth means little if one cannot perform meaningful tasks while there. To this end, the offshore industry can be given credit for moving ROV technology from the days of lost vehicles bobbing away on the waves to the present level of maturity and high reliability. In the early days, an ROV operator was happy just to get his system back on board safely, but today, modern ROVs work round the clock offshore, logging hundreds of hours without a system failure. For example, Sonsub used a 75 hp *Triton* for offshore work on the Ram-Powell Tension Leg Platform with no mechanical down time during 1,100 hours of dive time in 3,200 foot depths. Also, Sonsub International's *Triton* XL8 was used on Shell Deepwater's

Mensa field, recording over 5,000 hours of dive time with 90 per cent at depths beyond 5,000 ft. These are just a couple of the examples coming from the oil patch that underscore the high reliability of modern work class ROVs. The work class ROVs that are supplying this capability—the offshore workhorses—will be discussed in the next section.

THE WORKHORSES

There are several classes of ROV. They range from small low cost vehicles that are used for shallow water inspection and work tasks, through light work vehicles that cover a variety of tasks, up to the primary work class vehicle, that is used to accomplish most of the unmanned vehicle work offshore.

Work class vehicles can be broken down by depth capability and horsepower, with the majority of them being used for current deepwater operations to 2,500 m. With new requirements such as subsea tie-in operations on deepwater installations and the transportation of 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 2.4 m tall when a tool package has been installed underneath the ROV. Such heavy work class vehicles typically have a 100–250 horsepower range and a through-frame lift capability up to 5,000 kg—the distinguishing feature between medium and large ROVs. The vehicles range in weight (without work packages) from about 2,000–6,500 kg. Perry Tritech's *Triton* XL (Figure 1) is an excellent example of a heavy work class vehicle.

Table 1 (White, 1998) provides the result of a 1998 survey of commercial ROV operators. At that time, 415 work class ROVs were in operation. Many more were on the production line with Oceaneering planning to increase their fleet by 20 vehicles and Sonsub adding 12 more over a two year period. Based on such production schedules, the number of work class ROVs operating worldwide at the beginning of the year 2000 should be nearing 500 vehicles. Table 2 (Wernli, R.L. (editor), *Operational Effectiveness of Unmanned Underwater Systems*, table contributed by Daniel White) provides a representative listing of large work class ROVs along with pertinent operational specifications.

As offshore oil exploration and production pushes into deeper depths, new ROV requirements are emerging. Accordingly, there is a new generation of work class ROVs being developed for the oil and gas industry that have the capability to perform work tasks to 3,000 m depths. These vehicles, while retaining the power and lift capabilities of the large, heavy work class systems, are being built into smaller frames while using more advanced technology aimed at keeping the umbilical size to a minimum. What distinguishes these advanced ROVs from their deeper diving cousins (*ATV*, *KAIKO*) is that, unlike the deep diving ROVs that carry only minimal power plants, allowing umbilical size (diameter) reduction, 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. Only a few of these vehicles have been completed, specifically for oil field applications, and include Perry Tritech's *Triton ST*, Hitec's *Stealth*, *HiROV* 3000 &

Figure 1 Perry Tritech's *Triton* XL

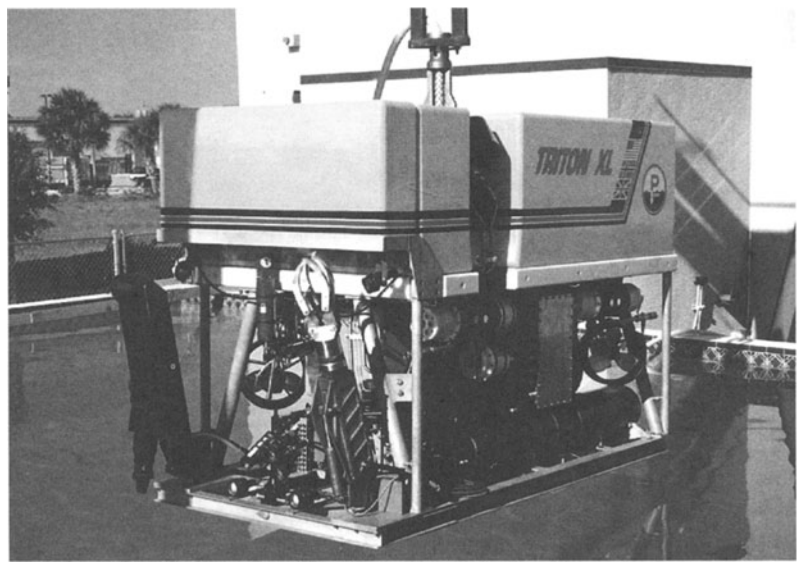


Table 1. Commerical Work Class ROVs

Oceaneering	89
Subsea	69
Stolt Comex Seaway	45
Sonsub	39
Racal	38
Dolphin a.s.	16
Coflexip Stena Offshore	14
Global Industries	13
DSND	12
Fugro UDI	9
Rovtech	8
STS	7
Canyon Offshore	5
Dominion Diving	5
Geoconsult	3
SBM	2
NTT	2
Cal Dive	2
Cable and Wireless marine	2
Others (estimated)	35
Total	415

Table 2. Largest Work Class ROVs

Manufacturer	Name	Size LxWxH-m	Depth-m	Power-hp	Wt.-kg	Payload-kg	Thru Frame
SubSea Offshore	Hercules	2.03×1.73×1.9	2000-3000	120	2200	150	n/a
Hydrovision	Demon	3.65×1.83×1.97	1000-3000	100	2800	300	3-tons
	Diablo	2.65×2.04×1.82	1000-3000	100	2600	300	3-tons
Slingsby Engineering	MRV	1.92×1.5×1.56	600-2000	75-200	to 2250	to 273	5-tons
Stolt Comex Seaway	SCV-100	3.1×1.8×1.8	1000	100	2900	200	5000 kg
Racal Techno Transfer	Sea Serpent		2500	160	2500		5000 kg
Seatec U/W Systems	Seatec RCU 230	3.4×2.3×2.4	1500	230	6500	500	n/a
Perry Tritech	Triton	2.46×1.45×1.6	1000	100	2450	227	3000 kg
	Triton XL	2.46×1.45×1.93	2500	100	3500	500	3000 kg
	Triton XL 250	2.46×1.45×1.93	2500	250	3500	500	3000 kg
Dolphin a.s.	Dolphin 2500	2.2×1.5×1.6	2500	100	2500	n/a	6000 kg
Mitsui	Dolphin 3K	2.85×1.96×1.94	3300	54	3700	150	n/a

HiROV 3500, Stolt Comex Seaway's *SCV*-3000, Oceaneering's *Magnum* and Slingsby's *Olympian*.

With offshore applications driving the workhorse ROVs toward perfection, will the industry ever require vehicles that can reach beyond 3,000 m? Essentially, the die has been cast, and as oil exploration goes deeper, it will continue to be supported by ROVs. Tasks for ROVs in support to deepwater pipelines, and oil and gas exploration and production, continue to increase in both depth and complexity. The exploration water depths in the Gulf of Mexico have more than doubled during the last two decades, increasing from depths of 1,067 m in 1976 to 2,316 m in 1996. As shown by the recent events that follow, exploration is already being carried out in water depths over 3,048 m, while production is quickly approaching that depth: (The list below is referenced in the *Operational Effectiveness of Unmanned Underwater Systems* CD-ROM.)

- Geoteam is performing surveys of the continental margin of Europe in water up to 4,800 m deep.
- Norway has discovered gas at 3,900 m in the Voring basin.
- Vanco Gabon Inc. and Reading & Bates Development Co. are planning ultra-deep exploration offshore of Gabon in 2,500 to 3,018 m.
- Transocean is building the 259-m drillship Discoverer Enterprise, which will be capable of exploratory drilling in depths to 3,048 m.
- Shell Offshore has contracted with Ray McDermott and Aker Marine for a spar style drilling rig capable of 3,048 m operations.
- Global Marine has converted the Glomar Explorer for drilling in over 3,000 m and Chevron has used the infamous ship to drill the deepest well in the world at 2,352 m in the Gulf of Mexico.

Will the trend to deeper water continue, and will offshore industry push their fleet of workhorse ROVs beyond the 3,000 m depth? There will probably be a few systems developed that reach such depths, however, offshore is ruled by the bottom line. If money can be made without going deeper, then that is where the work will remain. However, as the oil and gas reserves are depleted, and offshore operations reach beyond 3,000 m, you can bet that the ROVs will be there to support the effort. As the next section will verify, depth is no longer a limit. And, when combined with the reliability of today's workhorse vehicles, the technology will be there to perform the tasks when needed.

DEEP WATER ROVS

Although working to depths of 3,000 m is no small task, doubling that depth imparts a heavy toll on the overall system design. In particular, the added size and strength requirements of the umbilical can force the overall system beyond that which your average offshore operator can handle. One interesting aspect in deep ROV design is that, due to the generally lower current regime encountered in deep water, these vehicles tend to require less power, which aids the designer in keeping the umbilical diameters as small as possible. Because of the overwhelming size and cost of such deep ROV systems, they are typically found in military, government, or research organizations with missions, such as search and recovery, that are not necessarily driven by profit/loss statements.

Search and Recovery Missions

Search and recovery missions using ROVs is dominated by government/military establishments, primarily due to the magnitude of the problem, and the desire for the recovery of objects from any ocean depth. The magic number for the operational depth of such systems has always been 6,096 m, the depth that covers 98 percent of the ocean floor. Since search primarily involves semi-autonomous vehicles and towed systems, while recovery requires tethered ROVs, they will be discussed separately in the following sections.

Search

Underwater search has traditionally involved towed systems. These vehicles, such as Scripps Institution of Oceanography's *Deep Tow*—one of the first such systems—carry the necessary sonars, photographic equipment and other sensors required to locate everything from lost torpedoes and aircraft up to ships such as the *HMS Titanic.*

The primary method of operation for towed systems is to launch the usually very heavy vehicle 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 tow cables now include fiber optic communications that provide excellent bandwidth for the transmission of data from multiple sensors and TVs.

Many of the initial towed systems in the US 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 6,096 m or more, are provided in Table 3.

The Woods Hold Oceanographic Institution, which has been instrumental in locating long lost objects on the seafloor (*ARGO*-I lays claim to the discovery of the *HMS Titanic*) now operates the *ARGO*-II towfish (Bachmayer). The *ARGO*-II equipment and sensors are adjusted depending on cruise-specific requirements and additional equipment (e.g. magnetometer, transmissometer) can be installed. *ARGO*-II (figure 2) is a near-bottom towed vehicle—towed at altitudes of approximately 3 to 15 m above the seafloor—designed to operate to depths of 6,000 m. Its powered tether utilizes fiber optics to downlink controls to various subsystems and data sensors, and uplink digital data in both image format and as data-streams.

Towed systems have proven their worth many times over, however, 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 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. Both the French and the US Navy followed this approach when they decided to develop the *EPAULARD* (now retired) and the Advanced Unmanned Search System (*AUSS*), respectively.

The *AUSS* (figure 3) is a battery powered search system that can run autonomous search patterns to depths of 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 by 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

Table 3. Deep Towed Systems

VEHICLE	DESIGN DEPT	DEVELOPER/OPERATOR
SIS-3000	32,810 FT*	DATASONICS, U.S.
OKEAN	26,248 FT	NIPIOKEANBGEOFIZIKA INST., RUSSIA
DEEP OCEAN SEARCH & SURVEY SYSTEM (DOSS)	26,248 FT	OCEANEERING TECHNOLOGIES INC., U.S.
DEEP TOW (FISH 4, 5, & 6)	23,000 FT	MARINE PHYSICAL LABORATORY, U.S.
DEEP TOW	21,325 FT	JAMSTEC, JAPAN
OCEAN EXPLORER 6000	20,000 FT	OCEANEERING TECHNOLOGIES INC., U.S.
ORION	20,000 FT	OCEANEERING TECHNOLOGIES INC., U.S.
TOWED OCEANOGRAPHIC SURVEY SYSTEM (TOSS)	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	20,000 FT	CENTER OF OCEAN ENG LTD, BULARIA
RELIEF 4000	13,120 FT	CENTER OF OCEAN ENG LTD, BULARIA
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
AMS-60		SIMRAD/CHINA OCEAN MINERAL RESOURCES ASSOCIATION (COMRA), CHINA
DEEP TOWED SLEDGE	20,000 FT	DEEP OCEAN ENGINEERING, U.S., FOR COMRA, CHINA
SEAMARC		INTERNATIONAL SUBMARINE TECHNOLOGIES/WILLIAMSON & ASSOCIATES, U.S.
AMS-120 & 60		ACOUSTIC MARINE SYSTEMS/WILLIAMSON & ASSOCIATES, U.S.

*DEPTH WITH LARGE DIAMETER CABLE

search requirements can be made. After the object has been investigated, if required, the vehicle will automatically return to the point on the search track where it left off and continue the search. Figure 4 provides an example of acoustic data transmitted to the search team by the AUSS vehicle.

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 AUVs 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* (Ageev). This vehicle conducted a side-scan and photographic survey of the Soviet Yankee-class ballistic missile submarine that sank off Bermuda in 1986. Forty-five dives below 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 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.

A listing of AUVs operational around the world today can be found in the proceedings of OCEANS '99 MTS/IEEE (Wernli).

Recovery

The reason that one searches for an object is generally a desire to work on or recover it. For the military, it is usually the latter. Military aircraft and systems are continually falling into the world's oceans, often with classified payloads or nuclear weapons. When that happens, the military, regardless of the country, has a significant desire to recover the wreckage, or at least the most critical portions of it. To provide that ocean-wide capability, the military has developed the technology base necessary to field full ocean depth—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. The result of these programs,

Figure 2 WHOI's *ARGO II*

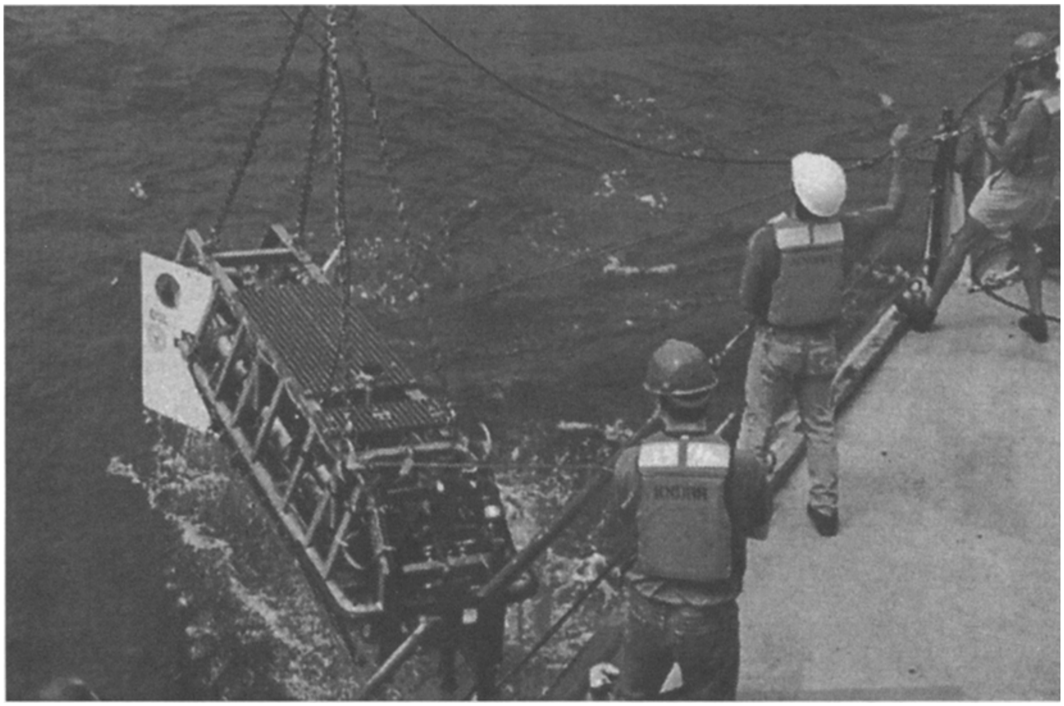
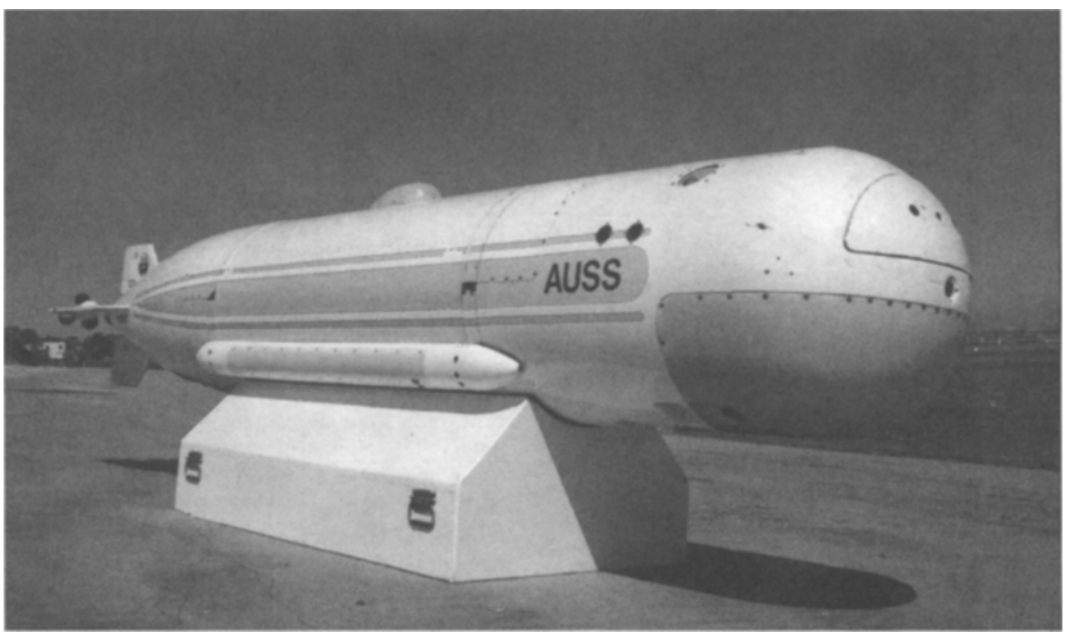


Figure 3 *AUSS*



augmented by technology developed for offshore oil field operations, has provided the capability to recover most desired items from the ocean floor.

The deep ocean recovery capability that exists in the US Navy continues to support recovery operations to depths of 20,000 ft (6,096 m), either through the use of the ATV operated out of SUBDEVRON5 or through Navy owned vehicles such as *CURV III* (figure 5), which is operated under contract. Oceaneering Technologies, Inc. presently has the support contract with the Navy. However, as shown in Table 4, there are several commercial systems now available that can be called in when necessary to support deep ocean operations. This impressive array of ROVs may not raise the *Titanic,* but they can get most missions accomplished.

Figure 4 *AUSS* Acoustic Data

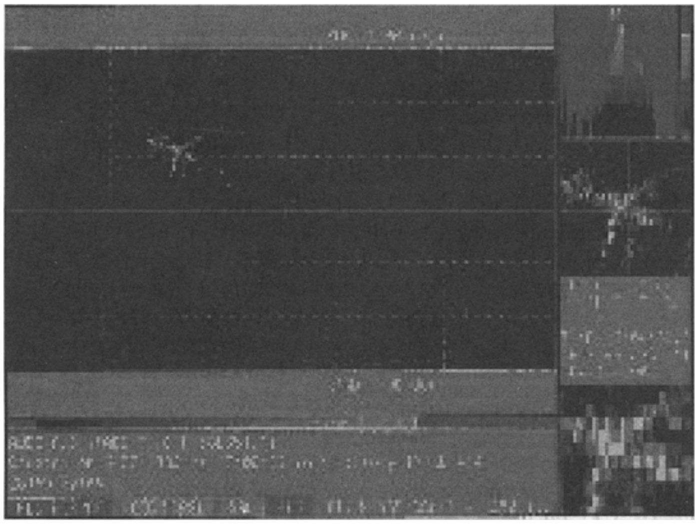
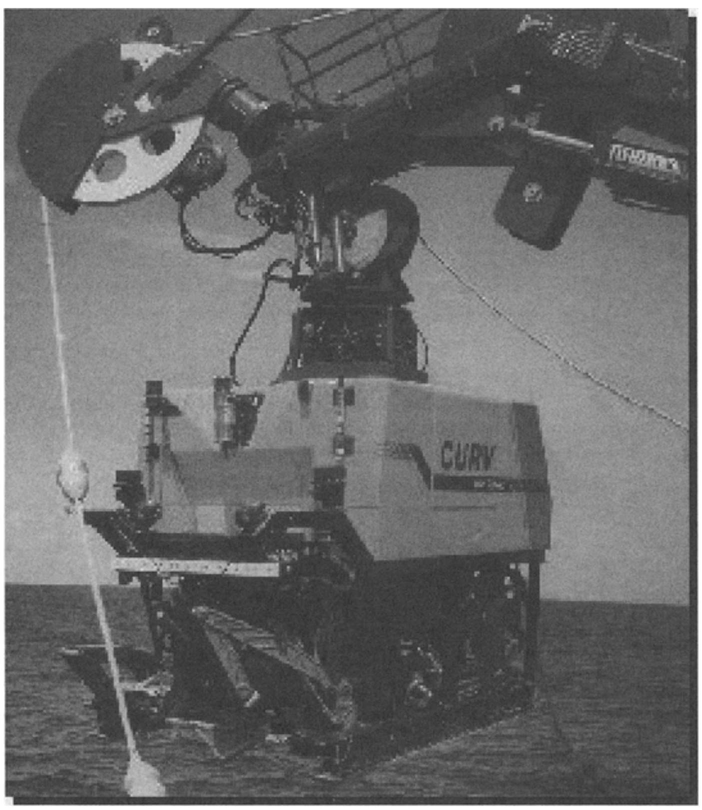


Figure 5 *CURV III*



Intelligence, Surveillance and Reconnaissance

Toward the end of the 1990's, 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 and between 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—as innerspace satellites (Wernli, 1994).

Although this new doctrine bodes well for missions requiring autonomous and semi-autonomous vehicles, which can travel far from the host platform, missions requiring deep tethered ROVs will be limited, if they exist at all. Because of this change of mission direction, the development of deep ROVs and related technology will probably stagnate for some time to come in the military environment. However, missions for AUVs should grow significantly as new vehicles such as the US Navy's Long Term Mine Reconnaissance System (LMRS), a submarine launched AUV, reach operational capability (Wernli, 1997).

Deep Ocean Research

Unlike the stagnation in deep ROV development in the military arena, the use of ROV technology for deep ocean research is growing dramatically. Technology has moved forward significantly since the early expeditions of the *H.M.S. Challenger* during the 1870s, when deep sea researchers first collected comprehensive samples of life in the deep ocean. 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, they don't provide the real time *in situ* observations available by the other methods, and in many cases, they damage or destroy the environment they are investigating. Many scientists still prefer manned submersibles. However, they are becoming rare, with existing systems, such as the US Navy's *Sea Cliff* and *Turtle*, being taken off line due to funding constraints. Thus, ROVs will provide the primary means of extending the researcher's reach into the depths, allowing the real-time acquisition of such deep-sea knowledge in the future. Today's technological sophistication of ROVs and camera sleds allows the biology and ecology of deep-sea habitats and organisms to be efficiently studied. Their ability to obtain high quality photographic and video documentation of dive sites in previously unobtainable locations provides the scientist with a wealth of data. The remainder of this section will discuss the unique capabilities and problems of some of the ROVs being developed or used for scientific research today.

Table 4. ROVs with Greater than 3,048 Meter Capability

VEHICLE	DESIGN DEPT	DEVELOPER
KAIKO*	11,000 M	MITSU/MITSUBISHI/KAWASAKI/JAMSTEC, JAPAN
ATV*	6,096 M	SPAWAR SYSTEMS CENTER, SAN DIEGO, U.S.
CURV III*	6,096 M	OCEANEERING TECHNOLOGIES INC., U.S.
MAGELLAN 725 & 825	7,000 & 7,620 M	OCEANEERING INTERNATIONAL INC., U.S.
GEMINI	6,096 M	OCEANEERING TECHNOLOGIES INC., U.S.
JASON/MEDEA	6,096 M	WOODS HOLE OCEANOGRAPHIC INST., U.S.
RTM 4000 & 6000	4,000 & 6,000 M	OKEANGEOFIZIKA, RUSSIA
SUPERMAX	6,000 M	DEEP SEA SYSTEMS INTERNATIONAL, U.S.
VICTOR 6000	6,000 M	IFREMER, FRANCE
HAMMERHEAD	5,000 M	SUBSEA INTERNATIONAL INC., U.S.
ROPOS	5,000 M	INTERNATIONAL SUBMARINE ENGINEERING, CANADA
TIBURON	4,000 M	MONTEREY BAY AQUARIUM RESEARCH INST., U.S.
HIROV 3500	3,500 M	HITEC SUBSEA AS, NORWAY
DOLPHIN 3K	3,429 M	MITSUI/JAMSTEC, JAPAN
HYSUB 75	3,300 M	INTERNATIONAL SUBMARINE ENGINEERING, CANADA
TRITON XL	3,500 M	PERRY TRITECH, INC., U.S.
MILLENNIUM	.3,000 M	OCEANEERING INTERNATIONAL INC., U.S.

*Only vehicles to exceed 6,096 M

Most ROV systems presently performing deep ocean science missions for the oceanographic community have been based on industrial systems that are adapted to scientific missions. One such example is MBARI's first ROV, *Ventana*, a *Hysub* system built by International Submarine Engineering (ISE) (described later in this section) (Robison). Similarly, the Canadian Scientific Submersible Facility operates a modified *Hysub* 5,000, now called ROPOS (Remotely Operated Platform for Ocean Science), which has been used in geological studies at locations such as the Juan de Fuca Ridge (Shepherd). Such commercially adapted electro-hydraulic vehicles have been criticized as awkward, noisy, destructive to the site under study, and inadequate in their data gathering and payload capabilities. These concerns have led researchers to develop vehicles such as WHOI's *Jason* and MBARI's new *Tiburon* ROVs, all-electric vehicles configured specifically for scientific research.

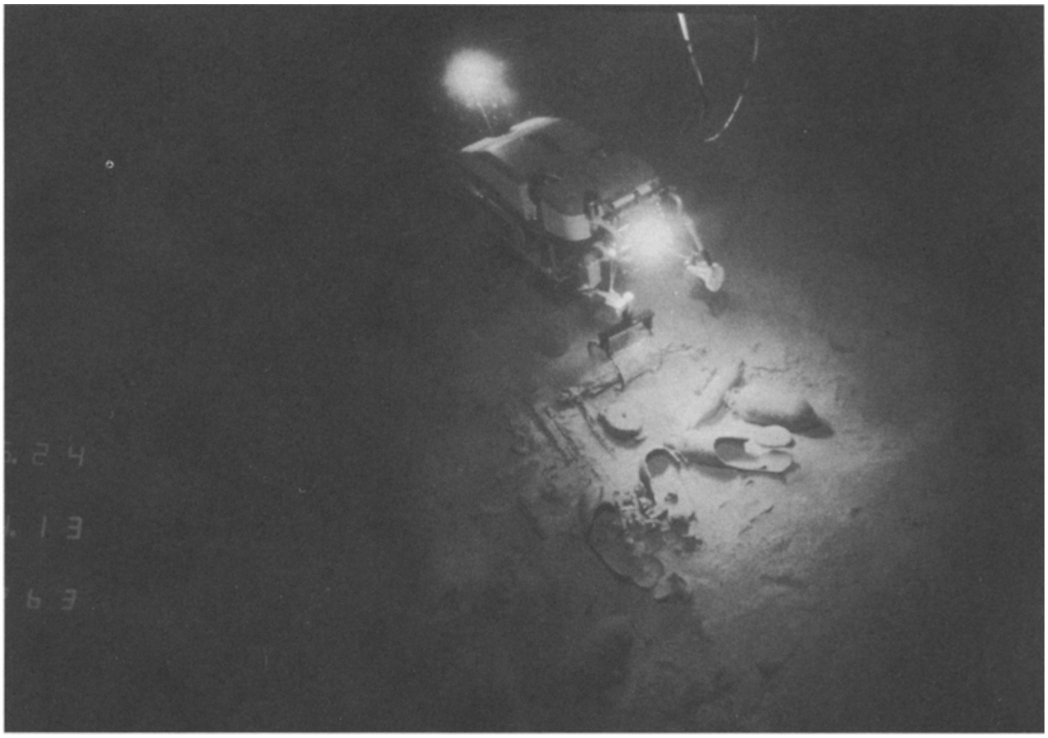
Even though its ancestors reach into the oil patch, MBARI's *Ventana* vehicle, a *Hysub* ATP-40 with upgraded cameras, sensors, sampling gear and telemetry, has been successfully conducting a variety of scientific investigations in and near the Monterey Submarine Canyon since 1988. Operating on a daily basis from Moss Landing, California, to depths as great as 1,460 m, *Ventana* has logged 7,818 hours and 1,653 dives as of August 1999. *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 WHOI's *Jason* vehicle. This 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, along with ancient shipwreck investigations in the Mediterranean Sea (figure 6). *Jason* is designed for detailed survey and sampling tasks that require a high degree of maneuverability. It weighs about 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, and uses electric motors for its pan/tilt and manipulator, thus avoiding the need for a noisy and less efficient hydraulic power system.

The *Jason* vehicle usually operates below the *Medea* vehicle during deeper missions. *Jason* is connected to *Medea* by a neutrally buoyant cable 15 mm in diameter and approximately 100 m long. The vehicles work together to provide lighting for each other in a fashion not commonly available in other submersible systems. The dual vehicle ROV system uses *Medea* as a wide area survey vehicle, which functions as a precision multi-sensory imaging and sampling platform. *Medea* weighs 363 kg in water and is maneuvered by controlling the surface ship's position within a dynamic positioning reference frame. *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.

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* (Newman). The mission requirements for the *Tiburon* ROV (figure 7) have driven most of the design decisions and the overall configuration of the system. The primary loca-

Figure 6 *Jason* performing archeological survey



tion for MBARI's research is in the Monterey Canyon, where the 4,000-m capability of the *Tiburon* will support investigations of geochemical processes, physics, geology and biology. 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. The ROV also 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. Missions for which the *Tiburon* is designed include:

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

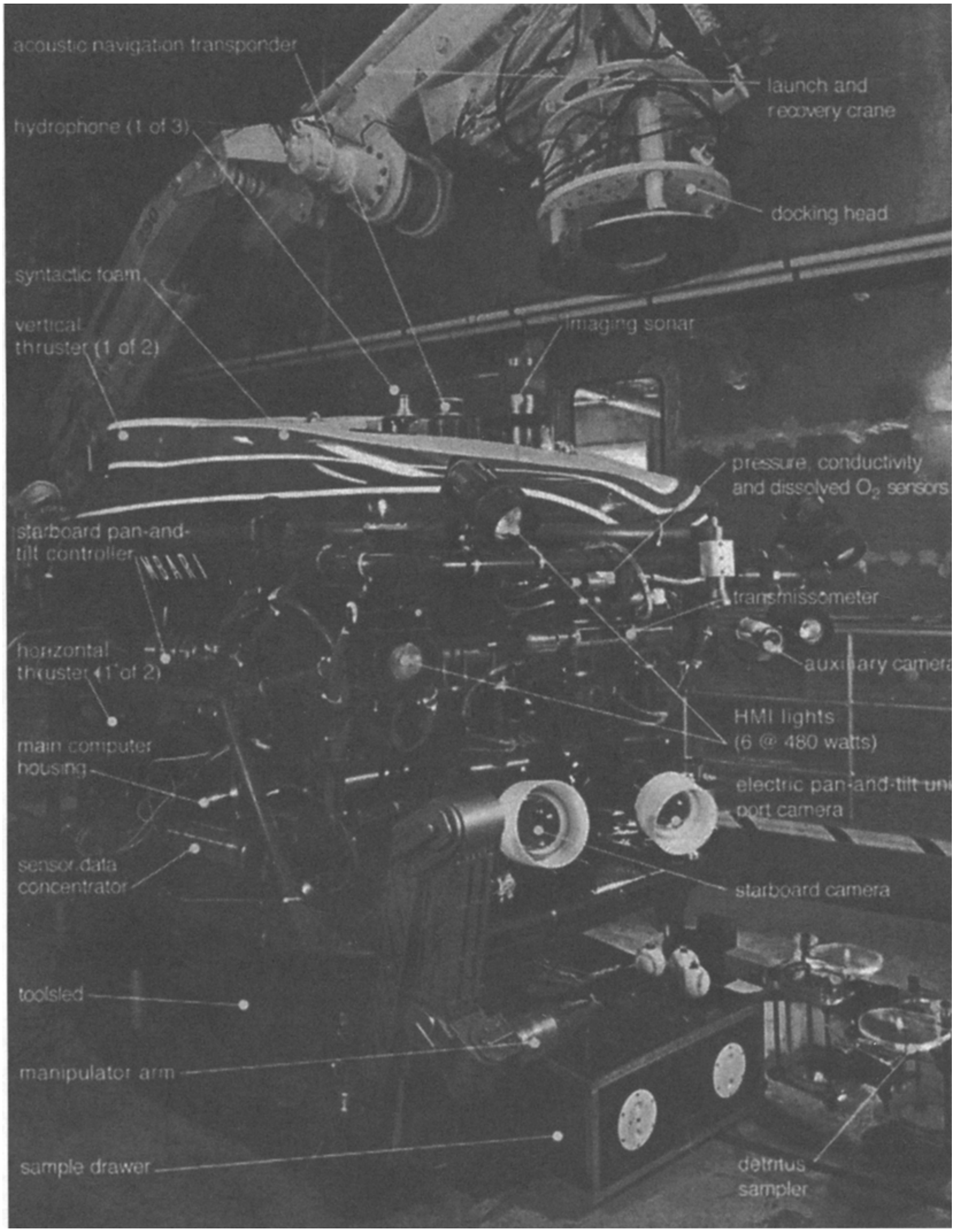
On all of its missions, the *Tiburon* performs as the front end of a data management system that supports general scientific use. Data from the core sensors on the ROV are made available to all of MBARI's scientific researchers. A detachable toolsled module can be configured for specific missions. Instrumentation 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

The United States is not the only country developing such advanced research ROVs. The Japan Marine Science and Technology Center (JAMSTEC) has developed a family of *Dolphin* ROVs for scientific missions and for recovery of the *Shinkai* manned submersibles. The *Dolphin* 3K, a 3,000 m ROV, has been used for geological and biological research operations. More recently, Japan has completed the development of the *KAIKO*, which has reached the deepest part of the ocean—10,911.4 m in the Mariana Trench.

Whereas reaching a depth of 6,000 m in the ocean was a tremendous feat by an ROV, the giant leap made by Japan in reaching a depth nearly twice that is truly phenomenal. The *KAIKO* (figures 8 and 9) is a two vehicle system: the launcher, which connects to the ship via the 12,000 meter electro-optic primary umbilical and also handles the 250 meter secondary cable to the vehicle, and the free swimming vehicle that can operate around the launcher within a

Figure 7 MBARI's ROV *Tiburon.*



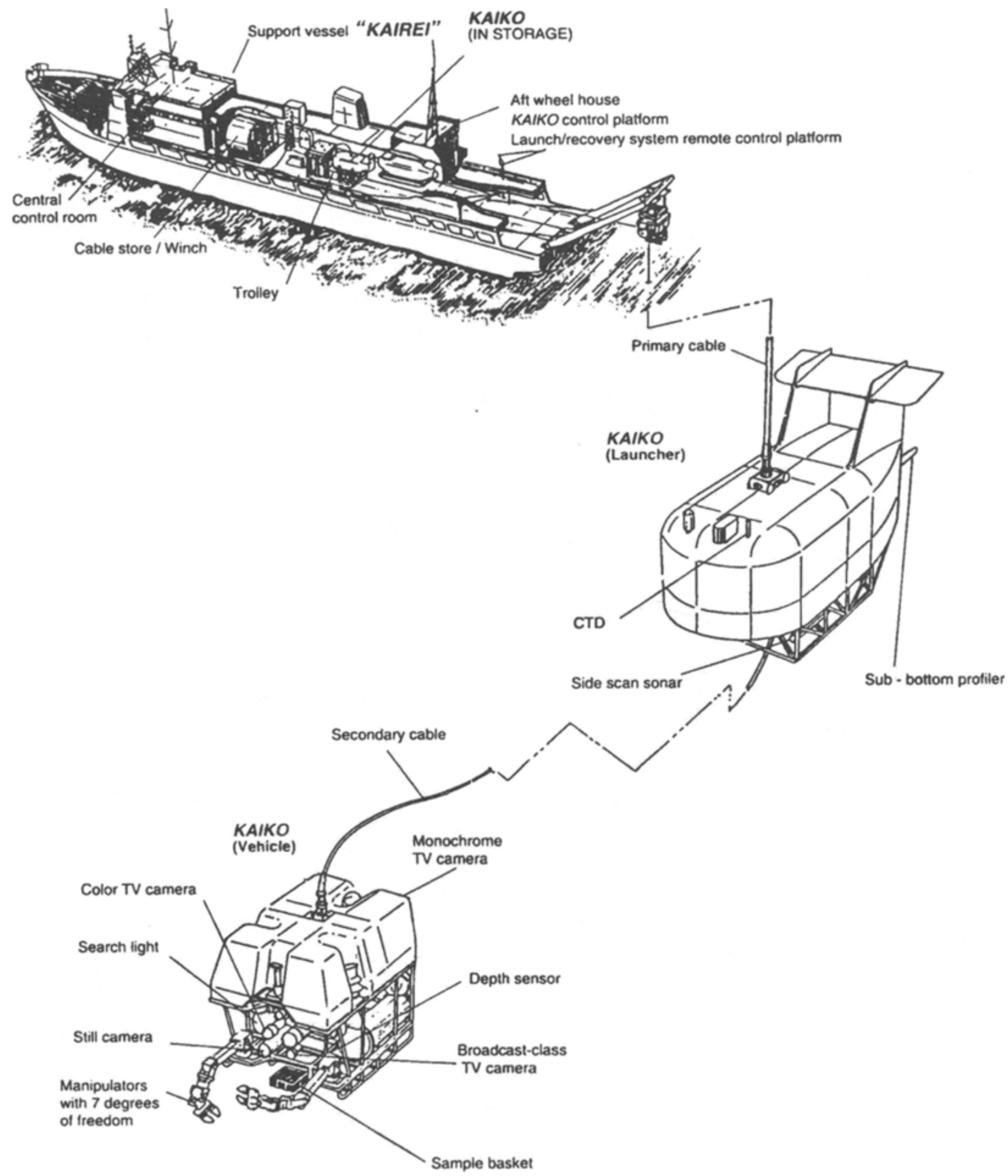
Greg Pio for MBARI © 1997

200-m radius (Tazaki). During vehicle operations, the *KAIKO* launcher normally hovers at a point 100 meters above the sea floor. Specifications on the vehicle and launcher are provided in table 5:

The *KAIKO* has three mission modes. The first is to survey the ocean floor down to a depth of 6,500 m by towing the system, which carries a side scan sonar and a sub bottom profiler on the launcher. This provides the capability to conduct sea floor topography and investigate the stratum beneath the sea floor. The free-swimming vehicle can use its TV cameras for precise survey of the sea floor.

The second mission is to extend the sea floor survey down to full ocean depth. In this case, the launcher is not towed, but hangs below the ship (depending on the current pro-

Figure 8 Japan's *KAIKO* ROV (schematic)



file) while the vehicle performs a precise survey of the ocean floor. And, the third mission is to provide a rescue capability for the *SHINKAI* 6500 manned submersible.

The *KAIKO*, which quite fittingly means "trench," completed its ultimate dive to the bottom of the Mariana Trench on March 24th, 1995. After a three hour trip, the vehicle reached the sea floor at 11°22.400' N and 142°35.550' E, where it conducted some research and left behind a calling card for future visitors, figure 10. The *KAIKO* will now operate from a new, dedicated deep sea research vessel called the *KAIREI* (which means "oceanic ridge").

In France, the French Institute of Research and Exploration of the Sea (IFREMER), long a developer and user of systems for deep exploration, has recently completed developing a 6,000-m ROV for scientific missions (Nokin). Named *Victor* 6000 (figure 11), the deep ROV is conceived to make optical investigations and to carry out local missions that include imagery, implementation of instrumentation and the sampling of water, sediments and rocks. The *Victor* 6000, which was developed for IFREMER by the ECA Group, a subsidiary of STN ATLAS Elektronik Group, has a depth capability of 6,000 m and a 1,320 lb payload capability. The all electric vehicle uses a 2,200 lb depressor that connects its 300 m neutrally buoyant tether to the 8,000 m umbilical.

THE FUTURE

From the past to the present, the capability and applications of ROVs have continued to increase. They have evolved from unreliable and expensive systems to highly reliable workhorses (albeit still expensive) that are continuing to set operational records offshore. Where will ROVs go in the future? Looking into the crystal ball and trying to focus on the future of deep water ROVs is blurry at best. However, some interesting observations can be made:

- The offshore industry will focus on ROVs to work down to depths of 3,000 m for the immediate future. The technology is there when they need to go deeper.
- The military is focusing on shallow water mine-countermeasures and littoral intelligence, surveillance and reconnaissance. Deeper water will remain a low priority.
- Vehicles will become simpler, and the equipment they mate and work with underwater will become more complex.
- Towed systems will continue to be a valuable asset for large-scale survey, but they will remain forever limited as "towed" systems.
- The cost of AUVs will continue to drop and their capability and acceptance will increase.
- On board energy storage will increase along with computational power.
- Electric ROVs and work systems will reach maturity and increase in number.
- The requirement, and need, for deep ocean exploration and research will increase.

Is there a trend here? I believe so. The ability to perform heavy duty work at full ocean depths has been proven—future applications become a design and finance problem. The trend that advancing technology is underscoring is a movement toward advanced semi-autonomous ROVs—capable systems that will have the ability to perform meaningful tasks to full ocean depths. Systems that will carry their energy with them, possibly recharging on the ocean floor, and communicate with the surface via ultra-small fiber optic umbilicals or acoustic modems. Such ROVs will still be able to perform complex tasks through the ability to mate with pre-installed underwater structures and equipment, or with other work packages sent to the ocean floor when required.

The all-electric ROV movement will spearhead many technological advancements in this area. Umbilical cables will get smaller, vehi-

Figure 9 Japan's *KAIKO* ROV (photo)

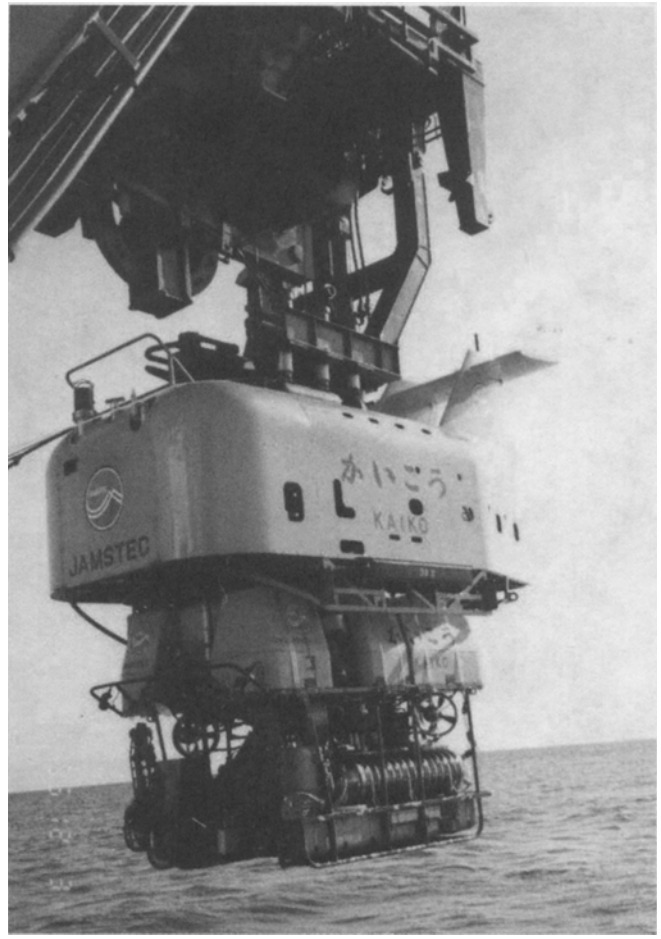
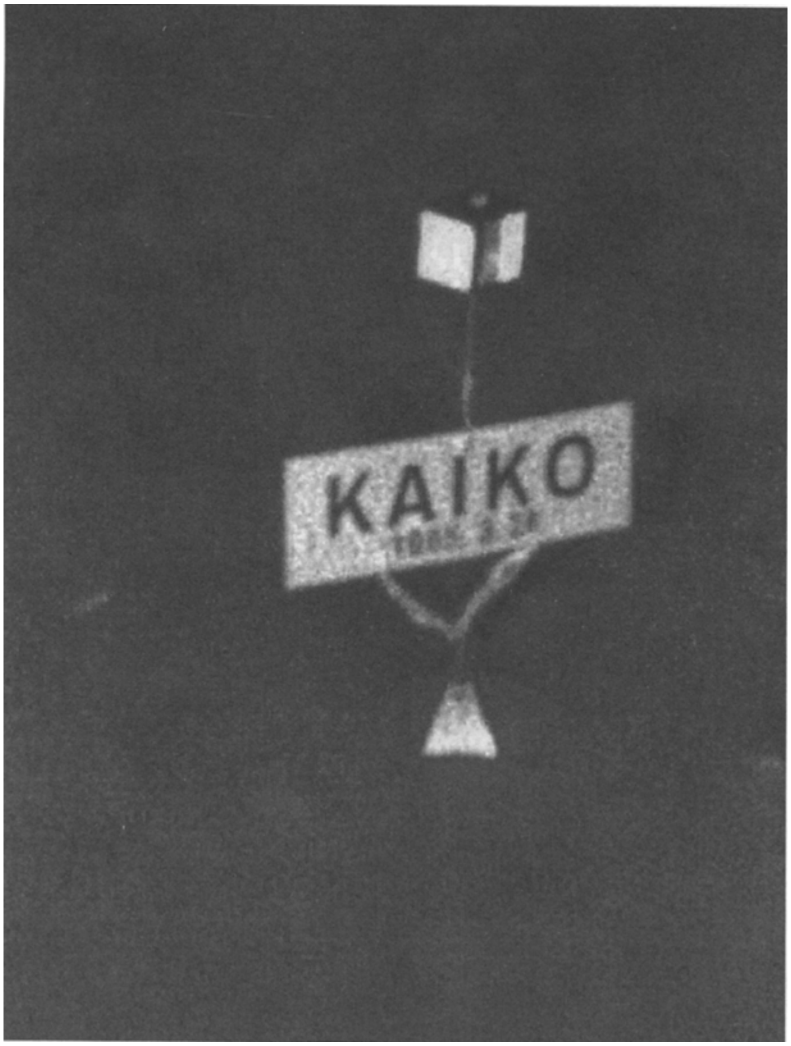


Table 5. KAIKO Specifications

Launcher	
• Dimensions:	1.52m L × 2.6m W × 2.0m H
• Weight:	5.3 tons (in air), 3.2 tons (in water)
• Tow Speed	1,5 knots
Vehicle	
• Dimensions:	3.1m L × 2.0m W × 2.3m H
• Weight:	5.6 tons (in air), −10kg (in water)
• Power:	Electro-hydraulic power, 45 kW
• Speed:	2 knots

Figure 10 *KAIKO's* Business Card



cle efficiencies will increase, the number of moving parts will be reduced and vehicle weights will decrease. At least ten companies or institutions are presently developing electric ROVs (White, 1999). One firm, ALSTOM Automation Schilling Robotics, in Davis, California, US, is pushing the envelop with a totally new class of all electric ROV called *Quest* (figure 12). And, designs for electric manipulators are probably waiting in the wings.

This all-electric technology base, when combined with the advanced image recognition and processing capability of the near future, will provide the next breakthrough in ROV development. As AUVs move toward real autonomy, the next logical step will be the marriage of the AUV and ROV. When that happens, the systems will evolve from vehicles that can be used for search and survey to systems capable of performing work in an unstructured environment.

Ultimately, there will be fixed installations where tethered and autonomous vehicles alike will perform their tasks, without the umbilical tied to a ship floating above. The number of work ROVs for offshore applications will continue to increase in the future. However, just as the bottom line has driven manned submersibles to the shore, the bottom line will drive the deep ROVs of the future toward miniaturized tethers, and semi-autonomous operation. Although the time line cannot be established with clarity, one projection can be confidently made—tethered, autonomous, and semi-autonomous ROVs will become abundant in the world's oceans in the decades to come, playing an ever increasing role in offshore operations, defense, and the understanding of Mother Earth.

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Figure 11 IFREMER's *Victor* 6000

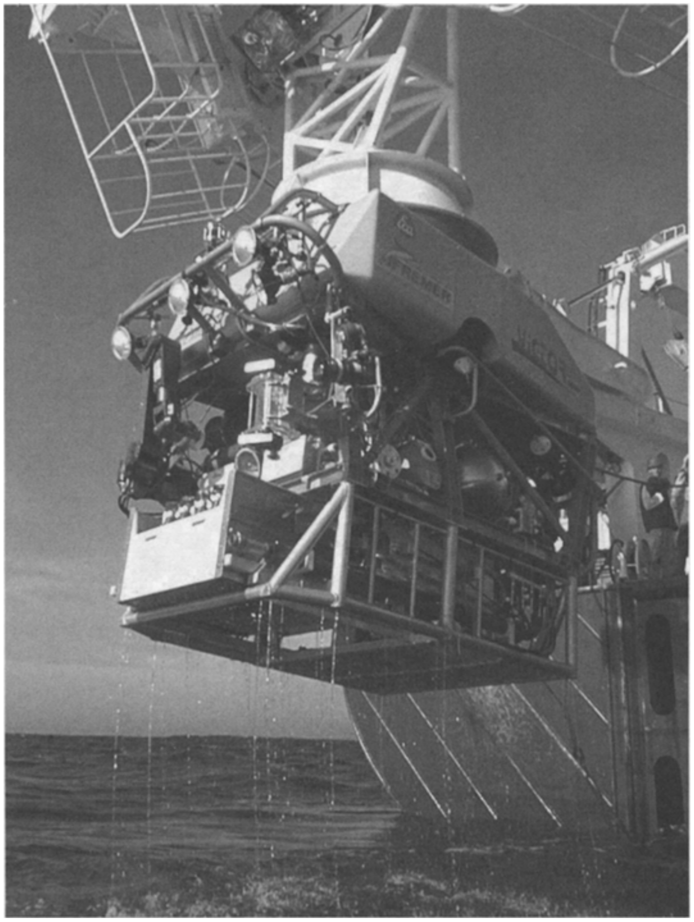

Figure 12 Schilling *Quest* Electric ROV

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