Preprint of an invited paper to appear in the Special Session on Industrial Robotics
IEEE 2000 International Conference on Robotics and Automation

Underwater Robotics: Out of the Research Laboratory and Into the Field

Louis L. Whitcomb[1]
Department of Mechanical Engineering
Johns Hopkins University

Abstract

The development of two new classes of commercial underwater robotic vehicles – deep diving work-class remotely operated vehicles and survey-class autonomous vehicles – is being driven by the needs of deep water oil production and deep ocean telecommunication cable operations. This paper presents a survey of the present state and future directions of commercial underwater robotics, examines principal technical challenges, and outlines new enabling technologies for commercial underwater robotic vehicles.

1 Introduction

Over 1000 robotic uninhabited undersea vehicles (UUVs) are presently in regular operation worldwide [35]. Most are commercial remotely operated vehicles (ROVs) designed to perform subsea inspection, survey, construction, and repair operations at modest (under 1000m) depths. The largest commercial manufacturers and operators have overall yearly revenues of \$10M to \$100M (\$US). Although difficult to estimate exactly, world-wide industry revenues directly related to underwater robot vehicles can conservatively be estimated at several hundred million dollars annually – principally in offshore oil field operations and seafloor pipeline and cable operations.

Underwater robots can now perform high-resolution acoustic and optical surveys in the deep ocean that previously were considered impractical or infeasible. For example, [45] reports a 1997 survey in which *Jason* and *Argo II* underwater vehicles were deployed to survey a 2 km^2 shipwreck site at 4100 m depth in the Pacific. This survey resulted in a detailed map of the site, 135,774 electronic still images (each covering about 7m×10m), and hundreds of hours of conventional and high-definition video.

The technical obstacles to underwater robot work, however, differ from those in land, air, and space missions in several fundamental respects: First, the rapid attenuation of acoustic and electromagnetic radiation in seawater severely restricts the range (and field of view) of high resolution acoustic and optical sensors. In consequence, high-resolution underwater survey sensors must be submerged to the immediate vicinity of a survey site – in sharp contrast to airborne and space-based survey sensors systems. Moreover, radio navigation techniques commonly employed in air and space operations do not function undersea. Second, the high ambient pressure of the underwater environment poses formidable design challenges both for (inhabited) submarines and (uninhabited) robots. At present, only a few of the world's submarines are capable of diving beyond 1000 meters in depth. Only one present-day operational research submersible can dive to 6500 meters [22]; none can dive to the ocean's deepest depths of 11,000 meters. In contrast, numerous underwater robots operate to 6000 meters [2], and one is capable of 11,000 meters operation [23]. Finally, in the case of untethered vehicles, underwater missions are limited not only by on-board battery storage capacity, but also by the severely limited bandwidth and delay inherent in underwater acoustic communication, the "intelligence" of on board control system, and payload capacity.

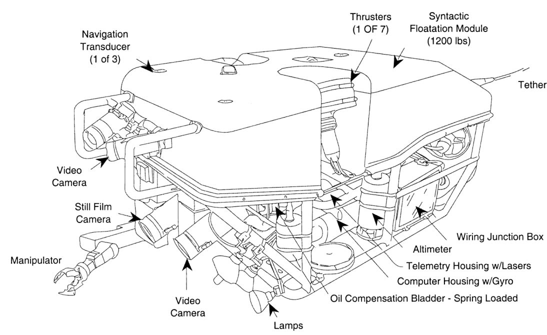

Figure 1: *Jason*, a 6000 meter Remotely Operated Vehicle (ROV) for oceanographic research. JASON was developed and is operated by the National Deep Submergence Facility (NDSF) of the Woods Hole Oceanographic Institution (WHOI) for use by the U.S. oceanographic research community with support from the National Science Foundation and the Office of Naval Research [2].

1.1 State of the Art

Most present-day vehicles are Remotely Operated Vehicles (ROVs) – teleoperated vehicles employing an umbilical cable to carry both power and telemetry from a mother-ship to the vehicle**.** Figure 1 depicts the *Jason* ROV, a 6000m ROV developed for oceanographic science with development funding from the Office of Naval Research. Figure 2 depicts a typical ROV deployment [2]. A growing number of research vehicles are Autonomous Underwater Vehicles (AUVs) – which operate without an umbilical tether. Figure 3 depicts *ABE*, an AUV developed for oceanographic research [48]. Most UUVs fall into one or more of the four following operational "mission" categories:

[1] Whitcomb is with the Department of Mechanical Engineering, Johns Hopkins University, 123 Latrobe Hall 3400 North Charles Street, Baltimore, Maryland, 21218, http://robotics.me.jhu.edu/~llw, email: llw@jhu.edu.

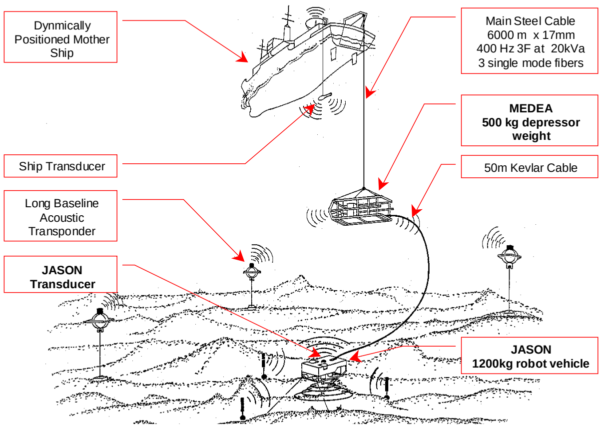

Figure 2: Typical ROV deployment showing the umbilical cable and depressor weight connecting the ROV to the mother-ship.

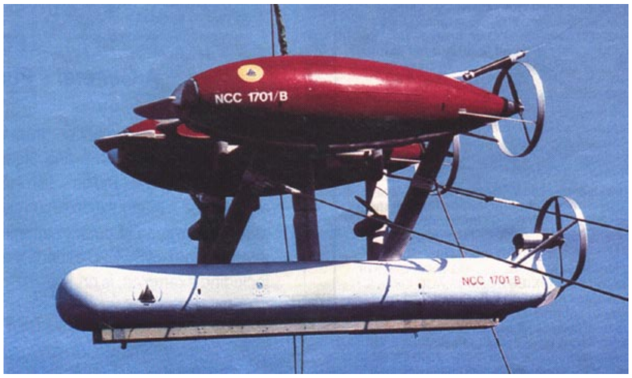

Figure 3: The Autonomous Benthic Explorer (ABE) is a 6000m Autonomous Undersea Vehicle (AUV) developed by WHOI for oceanographic research [48] with support from the National Science Foundation. Image credit WHOI, reproduced with permission.

1. **Commercial Missions:** Vehicles regularly deployed by industry to perform a huge variety of underwater tasks such as survey, inspection, search, object recovery, cutting, welding, cable burial, repair, and maintenance. Figures 5-8 and 11 show commercial UUVs.
2. **Oceanographic Research Missions:** Operational vehicles regularly deployed by research institutions for scientific research and exploration. The *Jason* ROV, Figure 1, has been in active use by the U.S. oceanographic research community since 1989 [2].
3. **Military Missions:** Vehicles for defense missions such as maintenance, inspection, survey, search, mine and ordinance reconnaissance, and recovery operations. For example: Over 7000 of the MK39 EMATT, an expendable military AUV developed by Sippican Inc., have been produced to date.
4. **Engineering Research:** Prototype vehicles principally developed as advanced prototypes for engineering research and development. The Naval Postgraduate School's *Pheonix* AUV, for example, is a well known research testbed vehicle [18].

The objective of this paper is to suggest future directions for commercial applications of underwater robotics, discuss the engineering obstacles, and review recent research developments in underwater robotics as indicators of future directions for commercial applications.

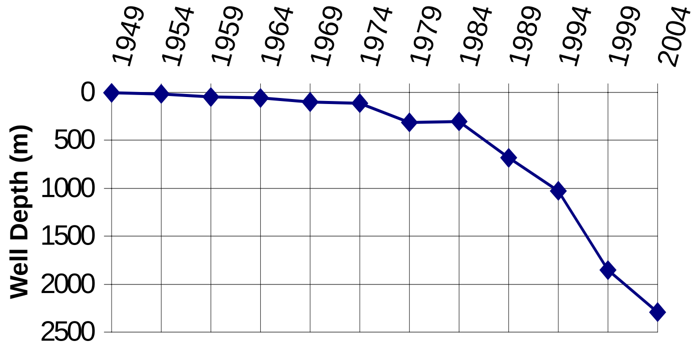

Figure 4: Offshore Oil Fields – maximum well depth versus year onstream. In 1949 the industry was producing in 5m water depth and it took a further 20 years to reach 100m (which is still the mean depth). The North Sea, then offshore Brazil, pushed the industry into deep waters and by 1989 production was occuring in 682m. Present plans suggest that by 2004, well will operate as deep as 2292m. Data and figure source: [17]. Reproduced with permission.

2 New Technology for New Missions

The offshore oil industry is now pursuing offshore oil production with well depths that previously would have been considered uneconomical or technically infeasible. Historically, the majority offshore oil production wells have been developed in water depths less than 300m, with most wells being 100m or shallower. Continued strong demand for oil, coupled with dwindling shallow-water oil reserves, has spurred the development of technically challenging deep water wells. A recent industry study, [17], Figure 7, suggests that production wells will be operating at depths to 2300m within the next five years. The practical depth limit for a human mixed gas diving is about 100m, or about 300m for full saturation diving. Below these depths, all survey, inspection, intervention, and repair operations must be executed either remotely with UUVs or with inhabited submersibles.

Underwater robotic vehicles are presently employed for two principal types of oil field missions: (1) subsea equipment installation, inspection, manipulation, and maintenance operations; and (2) sea-floor survey and inspection operations. At present, both missions are commonly executed with ROVs.

Figure 5: The *Magellan*tm ROV, an 8,000m 3,000 kg work-class ROV, was developed and is manufactured by Oceaneering International Inc. Image credit: Oceaneering International, reproduced with permission.

Figure 6: The *Quest* ROV a new 3,500m 1,700 kg work-class ROV from Alstom-Schilling Robotics, Inc. Image credit: Alstom-Schilling Robotics, Inc., reproduced with permission.

3 The Deep Diving Work-Class ROV

The oil-field mission of subsea equipment installation, inspection, manipulation, and maintenance demands large high-power ROVs equipped with powerful robotic arms, high-resolution cameras, and sophisticated tool packages to perform a variety of specialized tasks. These vehicles are commonly referred to as "work class" ROVs in the industry. The reader is directed to [35] for a comprehensive listing of work class ROVs, and to [36] for a gallery of recent vehicles.

This Section reviews fundamental "enabling technologies" that are critical factors in developing a new generation of deep water work class ROVs for ever-increasing operational depths.

3.1 Umbilical Cable Power Capacity:

Deep diving ROV system designs are dominated by cable limitations. Long umbilical cables severely limit the power available to deep-water ROVs. Work class ROVs for shallow-water operation are typically consume peak power of 35 to 150 kW (50-200 Horsepower). While level of power can easily be carried on short electricall umbilical cables, long cables severely limit the power deliverable to the vehicle in several ways. First, it is desirable to have umbilical of minimum possible diameter in order to reduce the cable's hydrodynamic drag. Umbilical diameters in the 17mm to 30mm range are typical. Second, given a maximum desired cable diameter, the maximum allowable voltage stress of cable insulation material places an upper bound on the supply voltage to the umbilical cable – typically to around 2000 V. Third, the transmission-line losses of a long cable are considerable – over 50% loss can occur in longer cables. In consequence the new class of deep-diving work-class ROVs must operate at lower vehicle power levels than their shallow-water predecessors.

Recently developed commercial vehicles exemplify the limitations imposed by long umbilical cables: The *Magellan*^{tm} 825, a 8,000m 3,000 kg work-class ROV, Figure 5, is rated at 18 kW (25 Hp), while the *Magnum*, its 3,000m counterpart, operates at up to 75 kW (100Hp).

Figure 7: .The *Max Rover* ROV, a fully electric 3000m, 800 kg work-class from Deep Sea Systems International, Inc. Image credit: Deep Sea Systems International, Inc., reproduced with permission.

3.2 Vehicle Power Efficiency:

Improved electro-mechanical efficiency is critical for deep-water ROVs under the power constraints inherent in long umbilical cables. Work-class ROVs have historically employed electro-hydraulic actuation for both manipulators and propulsors. This approach, originally pioneered on submersibles such as the *DSV Alvin* [13, 24], employs a single electric motor to drive a high-pressure hydraulic supply pump which, in turn, powers the entire suite of vehicle actuators including the vehicle's thrusters, robotic arm, and other articulated appendages. The this approach minimizes on-board electrical actuators (to a single motor) at the expense of the poor efficiency of electro-hydraulic actuation in comparison to direct electrical actuation.

In [24] the authors report a comparative analysis of the original electro-hydraulic propulsion system for the *DSV Alvin* with a subsequent upgrade to a fully electrically actuated propulsion system. The efficiency (defined as the ratio of shaft mechanical power output versus electrical power input) of the electro-hydraulic propulsors was 15%, while the efficiency of the fully electrical propulsion system was 43%. Improvements in propulsion efficiency directly improve critical vehicle performance parameters of lift capability and speed.

Electrically actuated thrusters have long been the norm for most small ROVs and all AUVs. We anticipate that electrically actuated thrusters will be the norm for the newly developing class of deep-diving "work-class" ROVs. Several recently developed work-class ROVs exemplify this trend:

The Alstom Automation Schilling Robotics *Quest* ROV, Figure 6, is a new 3,500m 1,700 kg work-class ROV employing novel electric thrusters. The novel rim-driven thrusters are distinguished by having just a single moving part and no rotating seals – a reduction in mechanical complexity that should provide high reliability.

The *Max Rover* ROV, Figure 7, developed and manufactured by Deep Sea Systems International, Inc., is a 3000m, 800 kg work-class ROV. This vehicle employs fully electric thrusters offering both high efficiency, compact size, and high reliability.

Figure 8: The *Talon* ROV, a 500m 55kg inspection ROV from Imetrix, is equipped with a high-precision 3-D acoustic navigation system and closed loop vehicle control system. Image Credit: Imetrix, Inc., reproduced with permission.

3.3 Power and Data Transmission:

Most work-class ROVs operate from three-phase or single-phase 60Hz or 400Hz AC power. At present, no industry-wide standard exists for ship-board vehicle power supplies, ground-fault isolation, ground-fault detection, on-vehicle power-conversion, rectification, and power distribution. ROV manufacturers employ custom in-house designs for their vehicle power systems.

Fiber-optic communication has rapidly become an industry standard for both data and video telemetry for work-class ROVs, having supplanted coaxial electrical telemetry in all deep-diving work-class ROV designs. Recently several manufacturers (Focal, Prism, Schilling) have offered purpose-built fiber-optic telemetry systems capable of carrying a variety of simultaneous data streams including digital I/O, Analog I/O, RS232, RS422, RS485, 10-Base-T Ethernet, and standard NTSC and PAL video.

The practical use of a conventional ROV telemetry system is complicated by three issues: pressure-housings, power, and cables/connectors. First, most telemetry systems are available as "card chassis", leaving the ROV designer to integrate the telemetry chassis with a spherical or cylindrical pressure housing. Second, the telemetry system must be intimately connected with a separate electrical power distribution system to provide power to both the telemetry and client devices. Third, a multitude of disparate watertight connectors and cables are typically employed to connect a telemetry system (in its own pressure housing) to sensors and actuators separately housed elsewhere on a vehicle.

To address these problems, researchers at the Monterey Bay Aquarium Research Institute (MBARI) have pioneered the development of a novel vehicle architecture in which power and telemetry distribution are unified in "data concentrator" modules [25, 26]. These modules provide single point control for device power, telemetry, and ground-fault monitoring. This approach has been implemented and tested at MBARI, and is reported in [27].

The recently announced Schilling Robotics "SeaNet" telemetry system takes the data-concentrator approach out of the research laboratory and into the commercial field. The SeaNet system is comprised of subsea telemetry "hubs", each with novel pressure housing, integral power, and complete telemetry electronics. Each hub supports four video channels and 26 bi-directional serial *or* digital channels and, moreover, each I/O channel is equipped with integral power distribution, ground fault detection, and switching. This system adopts a standard cable and connector for all I/O to client devices, thus minimizing sparing costs and focusing development on a single reliable connector. This standardized approach to telemetry and power distribution promises to yield advantages in cost, reliability, and ease-of-use.

As the UUV industry matures, we expect common industry standards for both power and telemetry distribution will be developed and adopted.

3.4 Navigation and Control:

Precision vehicle position sensing is an essential element of control and use of underwater robotic vehicles. It is impossible, for example, to precisely control a vehicle to within 0.1 meter tracking error when its position sensor is precise only to 10 meters. While research in control algorithms for underwater robots is rapidly advancing, e.g. [12, 15, 46], relatively few experimental implementations have been reported other than for altitude, depth, heading, or attitude control. Conspicuously rare are experimental results for X-Y control of vehicles in the horizontal plane. This lacuna is a result of the comparative ease with which depth, altitude, heading, and attitude are instrumented in comparison to X-Y horizontal position.

Virtually all large work-class ROVs are passively stable in roll and pitch, and are equipped with closed-loop heading and depth controllers. These heading and depth controllers are typically based on a conventional PD or PID control law. Very few commercial ROVs of any class are equipped with closed-loop XY position control – most are manually controlled (by the pilot) in the XY plane. Research by the author, collaborators, and other has demonstrated both acoustic time-of-flight and acoustic Doppler navigation systems to enable precision closed-loop XY control of underwater vehicles, e.g. [41, 42, 50]. Imetrix's *Talon* ROV, Figure 8, a 55 kg inspection-class ROV, is one of the few ROVs available with both an integrated high precision 3-D time-of-flight acoustic navigation system and a fully integrated closed-loop vehicle control system.

Recent field experience by the Author and collaborators with bottom-lock Doppler based navigation systems, [41], demonstrates that these Doppler systems are highly reliable and easily deployed navigation sensors which enable the implementation of closed-loop vehicle XY control. Closed-loop XY control provides improvements in precision station keeping, maneuvering, and trackline following, while reducing pilot workload. One recently announced work-class ROV, the Schilling *Quest* ROV, comes equipped with a standard bottom-lock Doppler sonar and full 3-D closed loop control. It is likely that this capability will become standard in future work-class ROV systems.

4 The Survey-Class AUV

The offshore oil production industry and the submarine telecommunication cable industry both have ongoing needs to perform bathymetric surveys of planned and existing subsea installation sites, and to visually inspect subsea equipment, pipelines, and cables. Some of these tasks will soon be routinely performed with AUVs.

Most present-day commercial survey and inspection operations are performed by surface ships and human divers in shallow water, and by remotely operated vehicles and tow-sleds in deep water. In addition to the usual sensors for vehicle depth, altitude, and attitude, survey vehicles are typically equipped with precision navigation instruments such as long-baseline acoustic navigation, short-baseline acoustic navigation, and inertial navigation. Commercial survey vehicles perform surveys and inspections with application-specific sensor packages such as the following: scanning pencil-beam and fan-beam sonars; multibeam sonars; sub-bottom profiling sonars; sidescan sonars; laser range finders; laser scanners; AC and DC magnetometers; electronic still cameras; 35mm cameras; video and HDTV cameras; ultrasonic thickness probes; and the like.

Although ROVs and tow-sleds presently dominate the deep water inspection and survey market, recent successes with research-class AUVs suggests their utility in survey tasks. In [47, 49] the authors report a highly successful program in which the *ABE* AUV, Figure 3, performed a high-resolution deep-water bathymetric survey of sea floor geological sites. In [5, 6] the authors report successful under-ice survey operations with the *Odyssey* AUV. In [39] the authors report successful survey operations with the *Hugin* AUV. The reader is directed to [43, 44] for an interesting survey of recent AUVs, and [40] for an analysis of their role in the offshore oil industry.

Several fundamental "enabling technologies" are critical factors in developing a new generation of deep water survey-class AUVs: power, communication, sensing, navigation, and control.

4.1 Power Storage

Finite power storage constraints represent the principal design obstacle to AUV system design. Principal design parameters are specific energy (energy storage per unit mass); energy density (energy storage per unit volume); charge/discharge voltage and current characteristics; and failure modes. Figure 9 compares the specific energy and energy density several chemical battery technologies.

Despite their modest specific energy and energy density, most present day AUVs employ conventional lead-acid [1, 10, 28] or nickel-cadmium [34, 39] battery cells. Most AUV designers employ conventional batteries for the following three reasons: (1) low cost; (2) ready availability in a variety of sizes and shapes; (3) ease of charging with minimum risk of fire and explosion. At present, only a few AUV's employ more exotic batteries such as silver-zinc batteries [5, 14] and aluminum-oxygen fuel cell battery [39]. The principal obstacles to widespread use of these novel battery technologies in AUVs are cost, fire and explosion safety, and pressure compensation.

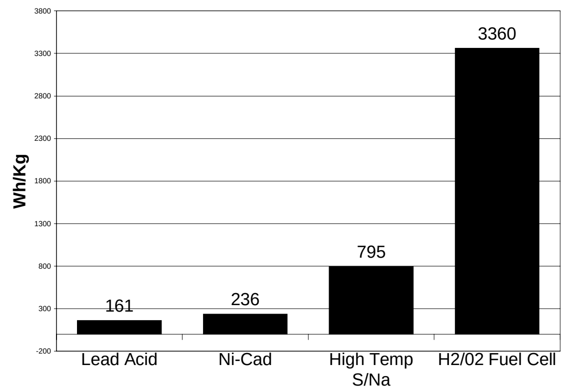

Figure 9: Theoretically attainable specific energy for several battery technologies. Note that practically attainable specific energy is often just 10% to 25% of these theoretical maximum values. Data source: [21].

4.2 Power Efficiency

High vehicle power efficiency is critical to successful AUV design. AUV designers typically distinguish two types of loads: propulsion load (including propulsion and control surface actuator loads); and the non-propulsion "hotel load" (including on-board computers, vehicle navigation sensors, and payload loads).

Propulsion Load: Propulsion load is minimized on survey-class AUVs through use low-drag hydrodynamic vehicle shapes, highly efficient electric thrusters, and slow survey speeds (typically under 10 knots). It is well known that, considering only propulsion load, the range of an underwater vehicle varies inversely with the square of the vehicle velocity [10].

Hotel Load: Hotel load is an important (and often overlooked issue) in AUV design. Figure 10, for example, shows the effective range of the ABE AUV as a function of speed for hotel loads varying from 10 W to 100 W [10, 33]. Reductions in hotel load are critically important for slow-speed missions.

AUV designers continue to benefit from advances in computational capability and reductions in power consumption commercial off-the-shelf (COTS) embedded computer systems. Although many present-day AUVs employ custom on-board computer systems, the trend is clearly toward industrial standard COTS embedded computer architectures such as the PC-104 standard.

The field of oceanographic sensors is undergoing dramatic advances. The last five years has seen the development of compact low power flux-gate compasses, fiber-optic and ring-laser gyroscopes, inertial navigation systems, Doppler current profilers, and other sonar systems and sensors that enable AUV missions previously considered impractical or infeasible. The trend is toward commercially available integrated low-power "stand-alone" sensor packages combining several sensors in a compact pre-calibrated housing with a single power connection and optically-isolated serial data telemetry.

Note that survey AUVs are not new. Several ultra-long range AUVs have been developed to perform long-term oceanographic surveys either by drifting passively [29] or by exploiting the ocean's vertical thermal structure for propulsion [37].

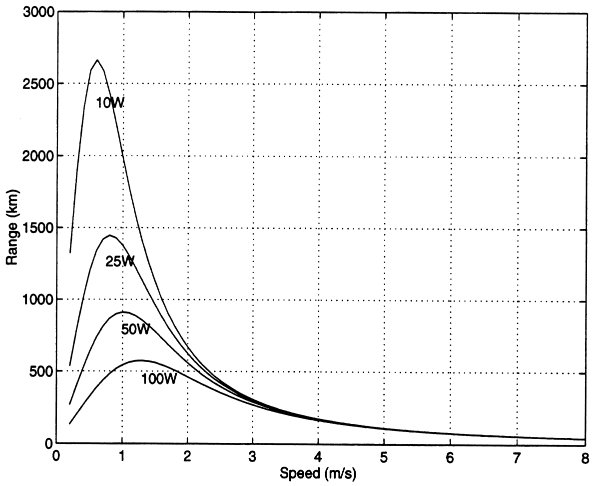

Figure 10: Range versus Speed for an ABE class AUV. Figure reprinted with premission from [33].

4.3 Acoustic Communication

Most survey-class AUVs operate semi-autonomously, maintaining an acoustic communication link with their human operators to periodically transmit vehicle status and to receive high-level commands. Although acoustic communication remains the only practical methodology for long-range communication in the ocean, they impose significant limitations. Subsea acoustic communication fundamentally limited by the speed of sound in water, about 1500 m/s, and by the fact that acoustic attenuation increases with sound frequency. In consequence, acoustic communication methods are inherently delayed, due to propagation delay, and have an effective bandwidth that decreases with range. A variety of companies (Datasonics, Simrad, Sonardyne) offer acoustic modems with modulation frequencies in the 1-50 kHz range, providing peak ranges of up to tens of kilometers with peak data rates typically up to about 2400-4800 Baud.

Recent research advances in low-power acoustic modem hardware and algorithm design, promise improved data rates and the possibility of simultaneously providing acoustic communication and positioning (navigation) with a single system [11, 16, 20]. This new class of low-power system combining both functions will be of great practical value in survey-class AUVs.

4.4 Multi-Beam Sonar

Recent reports of successful AUV survey missions suggests that bathymetric mapping (seafloor topography), sidescan imaging, magnetometer survey, and sub-bottom profiling will be the principal mission of the new survey-class AUVs [32, 33, 38, 39, 49]. Of these missions, bathymetric mapping and sidescan imaging appears to be of principal commercial interest.

Narrow-beam sonar is the most widely used sensing technique for 3-D bathymetric surveys. Narrow-beam scanning sonars typically either have a single narrow beam that is mechanically "pointed" or have multiple beams in a fixed transducer head. Beam widths are typically 1°-3°. Ping frequencies range from 12 kHz (full ocean depth ranges with accuracies of 10-100 meters) to 675 kHz (100 meter ranges with accuracies of 1-10cm. Sonar update rates are limited by the speed of sound in water, 1500 meters/second. The effective range resolution and area resolution of a single ping on the seafloor isdetermined by ping frequency and beam width. Sidescan sonars are used widely for 2-D searches and surveys, but relatively few sidescan systems are instrumented with the phase-sensitive transduction necessary for true 3-D bathymetry.

Several commercial sonar companies (Simrad, Imagenix, Reson) now offer low-power mechanically scanned or multibeam sonars suitable for deployment on AUVs. This is an area of intensive commercial competition and rapid industry evolution.

4.5 Navigation and Control

AUVs and ROVs both require reliable low-level navigation and control system in order to perform navigation and to control vehicle heading, depth, position, and attitude – as described in Section 3.4. Fully automating the task of on-board AUV navigation remains a formidable challenge. A variety of acoustic navigation decisions that are easily performed by a human operator are difficult to reliably automate. These include filter initialization for multipath signal rejection, initializing and reinitializing the system in case of a loss of acoustic returns for an appreciable period of time, and and LBL baseline crossings [47].

AUVs and ROVs both also require a "high-level" (or "mission-level") controller to sequence the execution of mission tasks, and to respond effectively to mission variabilities. Unlike ROVs, whose human pilot is the "high-level" controller, AUVs require at least a rudimentary automatic high-level control system. Despite over a decade of research in high-level control of AUVs [7-9, 18], no industry standard has yet evolved for high-level AUV control techniques. At present, most AUV employ fully custom control system programs developed in-house. Most of the present class of survey class AUVs will employ relatively simple high-level controllers enabling the operator to program a mission as a sequence of primitive tasks such as waypoint navigation, grid-searches, terrain following, pipeline following, docking, and undocking. These systems will also allow the operator to specify appropriate responses in reaction to expected events – i.e. "on loss of acoustic navigation, use dead-reckoning navigation." The problem of high-level AUV control remains an area of active research.

4.6 Robotic Arms for AUVs

We do not know how to effectively utilize robotic arms for manipulation from AUVs. The principal technical obstacle to teleoperated manipulation with AUVs is the low bandwidth and significant time delay inherent in acoustic subsea communication. The alternative of autonomous manipulation in unstructured environments remains an open research problem. In consequence, only a few research-class AUVs are equipped with robot manipulator arms, e.g.[51]. Unlike ROVs, where electro-hydraulic arms are the norm, the severe power constraints of AUV missions necessitate the use of energy-efficient electrically actuated arms. Recent research suggests the practical utility of a systems-level "teleprogramming" approach to teleoperation over the time-delayed bandwidth-limited links typical of acoustic communication [30, 31].

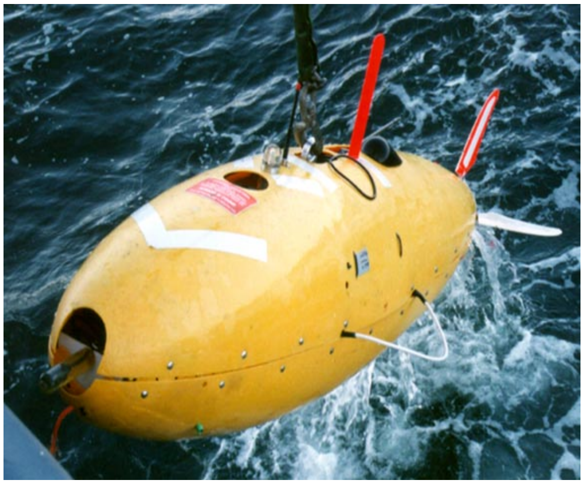

Figure 11: The *Odyssey II*, a 6000m AUV developed at the MIT AUV Lab. Bluefin Robotics Corporation and their *Odyssey III* vehicle design are a spinoff of the MIT *Odyssey* AUV research program [5]. Image credit: MIT AUV Lab, reproduced with permission.

4.7 Commercial Survey-Class AUVs

Within the last year, for the first time, several of the leading marine surveying and inspection firms have contracted with leading AUV developers for the manufacture and delivery of operational survey class AUVs. These include the following:

- In September 1999 C&C Technologies, Inc., a U.S. based marine survey firm, contracted with Kongsberg Simrad for a *Hugin* survey class AUV. *Hugin's* sensor suite includes a Simrad EM-2000 multibeam sonar for bathymetry and imagery, USBL, Doppler, and inertial navigation systems [3], and is powered with an aluminum-oxygen fuel cell battery [39]. The Simrad vehicle is a direct descendant of the Norwegian Defense Research Establisment's AUV research program [39].
- In September 1999 the Fugro Corporation, a leading international oilfield survey and service company, placed an order for a new survey-class AUV with International Submarine Engineering Ltd. (ISE) of British Columbia. Data collection systems on the vehicle will include multibeam bathymetry, sub-bottom profiler, side-scan sonar, and magnetometer [3]. ISE has developed several AUVs for the Canadian Department of National Defense and the Canadian Hydrographic Service, e.g. [14].
- In late 1998 Racal Survey, Ltd., a major marine survey firm based in the United Kingdom contracted with Bluefin Robotics Corporation for two 3000m survey class AUVs [4]. Bluefin Robotics Corporation and their *Odyssey III* vehicle design are spinoffs of MIT's *Odyssey* AUV program [5]. See Figure 11.

Several additional companies have also recently begun offering commercial survey class AUV's: Maridan, a Danish AUV company is producing the *Martin* vehicle for shallow water survey operations [19]. Sias/Patterson Inc., a U.S. AUV company, is offering the *Fetch* AUV for sensing and survey missions [28].

5 Conclusion

Two novel classes of commercial underwater vehicles: deep-diving work-class ROVs and survey class AUVs are entering production to meet the intervention and survey needs of two offshore industries – deepwater oil development and subsea telecommunication. The new markets are driving unprecedented development in the ROV industry, and are creating an AUV industry that has not existed previously.

The new deep-diving work-class ROVs will be designed to perform construction, maintenance, and survey/inspection operations to 3000 meters depths. They will increasingly employ fully electrically actuated propulsors and power management systems to effectively utilize the severely limited power available via long umbilical cables. Although electro-hydraulic manipulator arms will remain the standard due to their strength and reliability, fully electric arms will soon be available. These vehicles will employ fully fiber-optic telemetry systems to carry an increasingly sophisticated array of sonars and cameras. These ROVs will utilize the latest advances in doppler, inertial, and USBL navigation systems. Vehicle developers will be increasingly employ COTS integrated multi-function sensor packages rather than doing in-house custom integration of discrete sensors. New bottom-lock doppler systems will enable fully automatic closed-loop XY station-keeping and tracking control modes in addition to the usual auto-heading and auto-depth closed-loop control modes.

The new survey class AUVs constitute the first large-scale commercialization of AUVs – a long-anticipated watershed event for the AUV community. Survey-class AUVs are designed to perform multibeam bathymetric surveys, sidescan sonar imaging, sub-bottom profiling, and magnetometer surveys. These AUVs will be operated semi-autonomously, employing advanced acoustic modems to report system status and partial survey results in real-time to human operators, and to receive survey trajectory commands from human operators. COTS computer hardware will become the norm. The vehicles will employ simple and robust high-level ("mission-level") controllers, conventional low-level trajectory controllers, and sophisticated power management subsystems. Although many of these vehicles will initially employ conventional Ni-Cad batteries, recent advances in Li-ion and fuel-cell technology may offer alternatives.

Acknowledgements

The author gratefully acknowledges cogent suggestions provided by Dana Yoerger, Hanumant Singh, and Andrew Bowen of the Woods Hole Oceanographic Institution. Several organizations provided permission to reproduce images as noted in the captions. Douglas Westwood Associates graciously provided permission to reproduce Figure 4.

References

[1] B. Allen, R. Stokey, N. Forrester, R. Gouldsborough, M. Purcell, and C. von Alt, "REMUS: a small, low cost AUV; system description, field trials and performance results," in *Proceedings of IEEE/MTS OCEANS'97*, vol. 2, 1997, pp. 994-1000.

[2] R. Bachmayer, S. Humphris, D. Fornari, C. V. Dover, J. Howland, A. Bowen, R. Elder, T.Crook, D. Gleason, W. Sellers, and S. Lerner, "Oceanographic Research Using Remotely Operated Underwater Robotic Vehicles: Exploration of Hydrothermal Vent Sites On The Mid-Atlantic Ridge At 37 North 32 West," *Marine Technology Society Journal*, (32) 3:37-47, 1998.

[3] B. Barton, Editor, "AUV Orders Show Industry Committment," *Inertnational Ocean Systems Design*, (3) 5:15, 1999.

[4] B. Barton, Editor, "Racal Goes for Oracle," *International Ocean Systems*, (4) 1:15, 1999.

[5] J. Bellingham, C. Goudey, T. Consi, J. Bales, D. Atwood, J. Leonard, and C. Chryssostomidis, “A second generation survey AUV,” in *Proceedings of the 1994 IEEE Symposium on Autonomous Underwater Vehicle Technology*. Cambridge, 1994, pp. 148-155.

[6] J. G. Bellingham, “Arctic ocean hydrography using autonomous underwater vehicles,” MIT Sea Grant AUV Laboratory, Technical Report 1998.

[7] J. G. Bellingham and D. Humphrey, “Using layered control for supervisory control of underwater vehicles,” in *Intervention/ROV '90*, 1990, pp. 175-181.

[8] D. R. Blidberg, “Time-ordered architecture for knowledge-based guidance of an unmanned untethered submersible,” Proceedings of IEEE Oceans '84, pp. 571-575, Washington, DC, 1984.

[9] R. P. Bonasso, D. R. Yoerger, and W. K. Stewart, “Semi-Autonomous Underwater Vehicles for Shallow Water Mine Clearing,” Proceedings of the 1992 Symposium on Autonomous Underwater Vehicle Technology, pp. 22-28, Washington D.C., USA, 1992.

[10] A. M. Bradley, “Low Power Navigation and Control for Long Range Autonomous Underwater Vehicles,” Proceedings of the Second International Offshore and Polar Engineering Conference, pp. 473-478, 1992.

[11] V. Capellano and G. Jourdain, “Comparison of adaptive algorithms for multichannel adaptive equalizers. Application to underwater acoustic communications,” Proceedings of the IEEE Oceans '98 Conference, pp. 1178-1182, 1998.

[12] S. K. Choi and J. Yuh, “Experimental Study on a Lerning Control System with Bound Estimation for Underwater Robots,” Proc. IEEE Int. Conf. Robt. Aut., pp. 2160-2165, 1996.

[13] N. Estabrook, H. Wheeler, D. Uhler, and D. Hackman, “Development of deep-ocean work system,” *Mechanism and Machine Theory*, (12) 5:569-76, 1977.

[14] J. Ferguson, A. Pope, B. Butler, and R. I. Verrall, “Theseus AUV - two record breaking missions,” *Sea Technology*, (40) 2:65-70, 1999.

[15] T. I. Fossen, *Guidance and Control of Ocean Vehicles*. New York: John Wiley and Sons, 1994.

[16] L. Freitag, M. Grund, S. Singh, S. Smith, R. Christenson, L. Marquis, and J. Catipovic, “A bidirectional coherent acoustic communication system for underwater vehicles,” Proceedings of the IEEE Oceans '98 Conference, pp. 482-486, 1998.

[17] D. Harbinson and J. Westwood, “Deepwater Oil & Gas - An Overview Of The World Market,” Deep Ocean Technology Conference, New Orleans, 1998.

[18] A. J. Healey, D. B. Marco, R. B. McGhee, D. P. Brutzman, and R. Cristi, “Evaluation of the NPS PHOENIX autonomous underwater vehicle hybrid control system,” Proceedings of the 1995 American Control Conference, pp. 2954-2963, Seattle, WA, 1995.

[19] L. Henriksen, A. Bjerrum, and A. Ishoy, “Sea Trials of MARTIN - a European Survey AUV,” Proceedings of the IEEE/MTS Oceans 98 Conference, pp. 1439-45, San Diego, 1998.

[20] D. Herold and M. Johnson, “A compact underwater acoustic modem,” Proceedings of the 1994 Symposium on Autonomous Underwater Vehicle Technology, pp. 393-398, 1994.

[21] H. A. Kiehne, *Battery Technology Handbook*. New York: Marcel-Dekker, 1989.

[22] K. Kobayashi, “Principal characteristics of the up-to-date Japanese oceanographic research vessels,” in *Proceedings of IEEE/MTS Oceans'95*, vol. 1. San Diego, 1995, pp. 472-477.

[23] M. Kyo, E. Hiyazaki, S. Tsukioka, H. Ochi, Y. Amitani, T. Tsuchiya, T. Aoki, and S. Takegawa, “The sea trial of ``KAIKO'', the full ocean depth research ROV,” in *Proceedings. OCEANS '95 MTS/IEEE*, 1995.

[24] R. Maloof, N. Forrester, and C. Albrecht, “A Brushless Electric Propulsion System for the Research Submersible Alvin,” Woods Hole Oceanographic Institution, Technical Report 1985.

[25] E. Mellinger, “Power system for new MBARI ROV,” Proceedings of OCEANS'93, pp. 152-157, 1993.

[26] E. Mellinger, A. Pierce, and M. Chaffe, “Distributed multiplexers for an ROV control and data system,” Proceedings of OCEANS'94, pp. 584-589, 1994.

[27] J. B. Newman and D. Stakes, “Tiburon: Development of an ROV for ocean science research,” Proceedings of OCEANS'94, pp. 483-488, 1994.

[28] M. R. Patterson and J. H. Sias, “Fetch (c) Commercial Autonomous Underwater Vehicle: A Modular Platform-Independent Architecture using Desktop Personal Computer Technology,” 1998 Marine Technology Society Ocean Community Conference, pp. 891-897, Baltimore, MD, 1998.

[29] T. Rossby, A. D. T. Voorhis, and D. Webb, “Quasi-Lagrangian Study Of Mid-Ocean Variability Using Long-Range SOFAR Floats,” *Journal of Marine Research*, (33) 3:355-382, 1975.

[30] C. A. Sayers, *Remote Control Robotics*. London: Springer-Verlag, 1998.

[31] C. P. Sayers, R. P. Paul, J. Catipovic, L. L. Whitcomb, and D. Yoerger, “Teleprogramming for Subsea Teleoperation using Acoustic Communication,” *IEEE Journal of Oceanic Engineering*, (23) 1:60-71, 1998.

[32] H. Singh, J. Catipovic, R. Eastwood, L. Freitag, H. Henricksen, F. Hover, D. Yoerger, J. Bellingham, and B. Moran, “An integrated approach to multiple AUV communications, navigation and docking,” Proceedings of the OCEANS 96 MTS/IEEE Conference, pp. 59-64, Fort Lauderdale, FL, USA, 1996.

[33] H. Singh, D. R. Yoerger, R. Bachmayer, A. M. Bradley, and W. K. Stewart, “Sonar Mapping with the Autonomous Benthic Explorer (ABE),” Proceedings of the the 9th International Symposium on Unmanned Untethered Submersible Technology, pp. 367-375, Durham, New-Hampshire, USA, 1995.

[34] S. M. Smith and J. Park, “Navigational data fusion in the Ocean Explorer autonomous underwater vehicles,” Proceedings of 1998 International Symposium on Underwater Technology, pp. 233-238, 1998.

[35] O. N. a. T. S. Staff, *Remotely Operated Vehicles of the World*. Palm City, Florida: Ocean News and Technology Press, 1998.

[36] U. M. Staff, “ROV Portfolio,” *Underwater Magazine*, (Winter 1999):33-41, 1999.

[37] H. Stommel, “The Slocum Mission,” *Oceanus*, (32) 4:93-96, 1989.

[38] M. A. Tivey, H. P. Johnson, A. M. Bradley, and D. R. Yoerger, “Thickness of a submarine lava flow determined from near-bottom magnetic field mapping by autonomous underwater vehicle,” *Geophysical Research Letters*, (25) 6:805-808, 1998.

[39] K. Vestgard, N. Storkersen, and J. Sortland, “Seabed Surveying with the Hugin AUV,” Proceedings of the the 11th International Symposium on Unmanned Untethered Submersible Technology, pp. 63-74, Durham, New-Hampshire, USA, 1999.

[40] J. Westwood, “Future Prospects for AUVs,” Maridan 'PING' Symposium, Copenhagen, 1999.

[41] L. L. Whitcomb, D. R. Yoerger, and H. Singh, “Advances in Doppler-Based Navigation of Underwater Robotic Vehicles,” Proceedings of the IEEE International Conference on Robotics and Automation, pp. 399-406, 1999.

[42] L. L. Whitcomb, D. R. Yoerger, H. Singh, and D. A. Mindell, “Towards Precision Robotic Maneuvering, Survey, and Manipulation in Unstructured Undersea Environments,” in *Robotics Research - The Eighth International Symposium*, Y. S. a. S. Hirose, Ed. London: Springer-Verlag, 1998, pp. 45-54.

[43] D. G. White, “Autonomous Undersea Vehicles Part 1: The Test Bed AUVs,” *Ocean News and Technology*, (July/August):30-32, 1999.

[44] D. G. White, “Autonomous Undersea Vehicles Part 2: AUVs for Search and Survey,” *Ocean News and Technology*, (September/October):30-32, 1999.

[45] R. A. Williams and R. Torchio, *M.V. Derbyshire Surveys --- UK/EC Assessors' Report: A Summary*. London: Department of the Environment, Transport and the Regions, Eland House,Bressenden Place, London SW1E 5DU, 1998.

[46] D. R. Yoerger, “Precise Control of Underwater Robots,” in *International Advanced Robotics Programme Workshop on Mobile Robots for SubSea Environments*. Monterey, CA, USA, 1990.

[47] D. R. Yoerger, A. M. Bradley, M.-H. Cormier, W. B. F. Ryan, and B. B. Walden, “High Resolution Mapping of a Fast Spreading Mid-Ocean Ridge with the Autonomous Benthic Explorer,” Proceedings of the the 11th International Symposium on Unmanned Untethered Submersible Technology, pp. 21-31, Durham, New-Hampshire, USA, 1999.

[48] D. R. Yoerger, A. M. Bradley, and B. B. Walden, “Autonomous Benthic Explorer, Deep Ocean Scientific AUV for Seafloor Exploration: Untethered, On Station One Year Without Support Ship,” *Sea Technology*, (33) 1:50-54, 1992.

[49] D. R. Yoerger, A. M. Bradley, B. B. Walden, M.-H. Cromier, and W. Ryan, “Fine-Scale Seafloor Survey in Rugged Deep-Ocean Terrain with an Autonomous Robot,” in *Proc. IEEE Int. Conf. Robt. Aut.*, 2000.

[50] D. R. Yoerger and D. A. Mindell, “Precise Navigation and Control of an ROV at 2200 Meters Depth,” in *Proceedings of Intervention/ROV 92*. San Diego: MTS, 1992.

[51] J. Yuh and S. K. Choi, “Semi-Autonomous Underwater Vehcile for Interventions Missions: An AUV That Does More Than Just Swim,” *Sea Technology*, (40) 10:37-42, 1999.