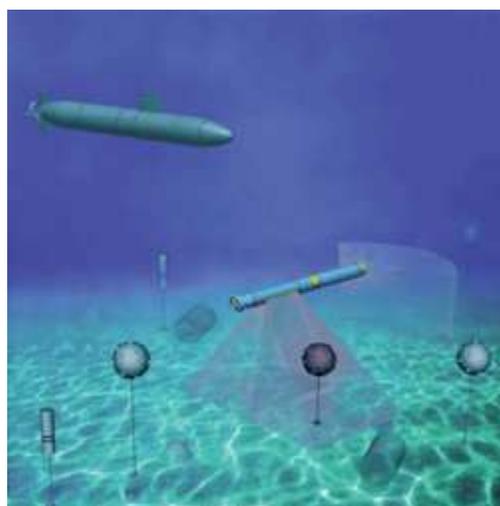


Unmanned Underwater Vehicles:

# BENEATH THE WAVE OF THE FUTURE

by Edward C. Whitman



The Long-Term Mine  
Reconnaissance System  
(LMRS) will be a torpedo  
tube-launched and  
tube-recovered underwater  
search and survey  
vehicle capable of performing  
autonomous  
minefield reconnaissance as  
much as 120 miles in  
advance of a host submarine.  
LMRS will be  
equipped with both forward-  
looking and  
side-scan sonars.

## **Introduction: Growing UUV Requirements**

As naval forces move decisively "...from the sea" into the littorals - facing shallow and constricted waters, asymmetric threats, and challenging mission requirements - going "in harm's way" to achieve access will become increasingly hazardous for naval platform and their crews. This is a particular concern for the Submarine Force, which will often be "first in" to carry out intelligence, surveillance, and reconnaissance (ISR) missions prior to hostilities and to serve as the Navy's primary "first strike" asset after they commence. For this reason, the Navy has been active over several decades in developing unmanned underwater vehicles (UUVs) as adjuncts to conventional manned platforms in many of the submarine missions that arise in expeditionary warfare. Although initial emphasis is on minefield reconnaissance, intelligence collection, trailing, tagging, deception, and attack capabilities are potential future options, with command modalities that range from simple remote control to near-total autonomy. And not surprisingly, UUVs have emerged as a key element in future concepts of operations for the submarine community, beginning with the Long Term Mine Reconnaissance System (LMRS) and its successor, the Mission Reconfigurable UUV (MRUUV).

Since, strictly speaking, every self-propelled torpedo is also a UUV, unmanned underwater vehicles can trace their history back for more than a hundred years. More recently, mobile underwater targets, such as the Mk 39 Expendable Mobile ASW Training Target (EMATT) have demonstrated rudimentary UUV capabilities little different in their essentials from those of advanced UUV systems today. However, it is only in the last thirty years that progress in propulsion, control, hydrodynamics, and sensor technology have enabled the development of more broadly capable vehicles and freed the imagination of naval planners to propose new and innovative operational applications for them. The growing military potential of these platforms - particularly autonomous UUVs - stimulated the publication of a Navy UUV plan two years ago, and that document remains an authoritative and useful roadmap for supporting a wide range of naval missions, such as:

- Maritime Reconnaissance

- Undersea Search and Survey
- Communications/Navigation Aids o Submarine Track & Trail

Most of these roles are motivated by the unique advantages of underwater stealth and the need to manage risk, but there are many missions in which using UUVs to complement crewed platforms provides either a significant force-multiplier or simply a more cost-effective way of getting things done.

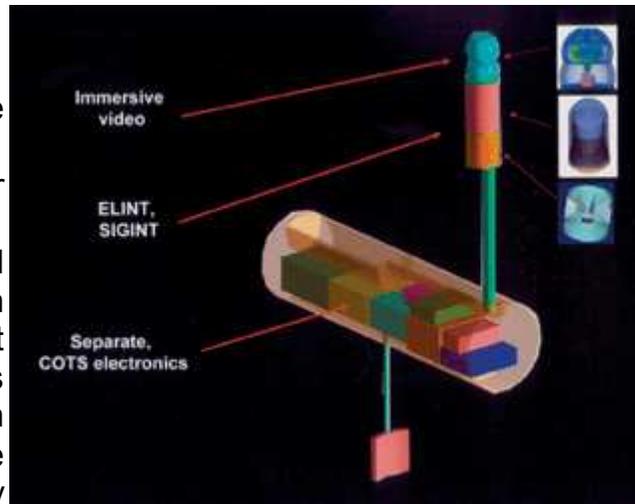
## **A Legacy of Development – Government, Academia, and Industry**

Despite the fact that UUVs are only now nearing operational use in the Navy, significant research and development programs on UUV concepts stretch back well over two decades. For example, the Defense Advanced Research Projects Agency (DARPA) supported a vigorous effort in the late 1970s and early 1980s to determine the feasibility of very long-endurance autonomous vehicles capable of undertaking Cold War surveillance missions over oceanic distances. DARPA investigated a number of promising energy-storage and propulsion schemes, but only drag reduction seemed to offer the possibility of achieving long range and endurance, and a variety of low-drag approaches, including bulbous, non-cylindrical bodies, were tried without achieving a practical vehicle. At that time, the principal barrier to fielding militarily-useful UUVs lay in storing enough energy for adequate range, but navigating accurately over long distances, communicating with host platforms, and implementing reliable autonomous control presented challenges of their own.

Although new high energy-density batteries such as lithium thionyl chloride cells are now available to satisfy many of today's propulsion requirements, their considerable expense per mission-mile is a serious disadvantage. Moreover, energy storage remains a significant factor in designing long-endurance UUVs for future military applications like tracking and trailing. However, with the introduction of small, low-powered inertial navigation components, the Global Positioning System (GPS), suitable satellite communications, compact antennas, more capable underwater sensors, and powerful digital information processing, many other barriers to implementing quite ambitious UUV

capabilities have fallen away. As long as their concepts of operation permit sporadic excursions near the surface to expose communications and navigation antennas or to allow access to relay platforms, only speed, endurance, and the adequacy of onboard autonomous control and “decision-making” will limit what UUVs can do.

The follow-on to LMRS, the Mission Reconfigurable UUV (MRUUV), will use modular payload packages, like this “ISR Mast,” which would provide the capability for both 360-degree optical surveillance at the surface, as well as ELINT/SIGINT collection. Still in the conceptual design stage, the first MRUUV “flight” will likely appear in 2009.



Since the DARPA investigations of several decades ago, a growing number of researchers in both academia and industry have sought to exploit these new technologies to create UUVs of their own and to support ongoing development programs, such as the Navy's efforts on LMRS and MRUUV. The Office of Naval Research (ONR), for example, has supported a broadly-based program to develop new autonomous UUV concepts, components, and applications for naval missions. In cooperation with the Naval Oceanographic Office (NAVOCEANO), ONR periodically stages an “AUV Fest” in the Gulf of Mexico off Gulfport, Mississippi, to give researchers the opportunity to demonstrate new technologies in accomplishing a standardized set of useful tasks, such as bottom-mapping and searching for mine-like objects. (Here, AUV means *autonomous* underwater vehicle, a designation that has also been

adopted by industry.)



This prototype UUV is under development to carry advanced sensor systems on near-shore missions in expeditionary warfare scenarios.

Among the evolving UUV systems that have been demonstrated to date are Woods Hole Oceanographic Institution's REMUS (Remote Environmental Monitoring Units), MIT's Odyssey, Florida Atlantic University's Ocean Explorer series, and the Naval Postgraduate School's Phoenix. Of these, the small REMUS vehicles – only 7.5 inches in diameter, five to seven feet long, and less than 75 pounds – inhabit the “low-end” of the UUV size spectrum, but over ten have been fielded, largely for oceanographic measurements. Powered by lithium batteries, REMUS variants have successfully completed survey missions of nearly 50 miles in the open ocean at three knots, and they have also demonstrated a capability to home in on a docking cone for downloading data and recharging their batteries at sea.

Somewhat larger are the Phoenix, Ocean Explorer, and Odyssey vehicles – on the order of a foot or two in diameter, seven to ten feet long, and 500 to 1,000 pounds. All have demonstrated range capabilities of 40-60 nautical miles at three to four knots, depending on payload, the most common of which has been

side-scan sonar. These vehicles have also carried a number of other instruments for various applications, and contact with their controllers is normally established with some combination of acoustic and satellite communications. Similarly, navigation systems using a combination of GPS and inertial references are commonly fitted, although several vehicles have used fixed acoustic transponders to triangulate their positions.

Not surprisingly, interest in using UUVs in private industry is growing simultaneously, and internationally, at least a half-dozen firms have begun to commercialize UUV technology developed in university and military laboratories. Currently, several vehicles are available for sale on the world market, and some developers also offer UUV services to the oil, undersea mining, and submarine cable industries for detailed bottom mapping, surveying, and geological exploration. In many applications, the UUV approach costs less than half that of a typical deep-towed system covering the same area – and, these vehicles can, and have, gone places that towed systems cannot, such as under the Arctic ice. Typically, the AUVs offered for commercial services by companies such as Maridan of Denmark and Hugin of Norway have been relatively small – generally about 15 feet long and several thousand pounds – and they offer endurance on rechargeable batteries of perhaps 20 hours at three or four knots. A variety of sensors can be fitted.



Typical of a commercial UUV used for bottom exploration is the Danish-built Maridan 600, shown here being recovered aboard a survey vessel. The 600 is approximately 15 feet long, weighs just under two tons, and boasts underwater

endurance of 10 to 60 hours at three knots, depending on the type of batteries fitted.

## **“Small is Beautiful” – but not always: LMRS and MRUUV**

Since most oceanographic investigations and typical bottom-mapping assignments pose relatively modest endurance and distance requirements, many academic UUV researchers and industry AUV service providers have adopted a “small is beautiful” design philosophy to minimize cost, turn-around time, and operating expense. In contrast, for military and naval missions, where long endurance and large, multi-purpose payloads are key goals, the trend for the future is toward larger and larger vehicles. The DARPA UUV program described above, for example, ultimately developed and tested several experimental craft that were extremely large for their time – 38 inches in diameter, 27 feet long, and approximately five tons displacement. These vehicles were transitioned to the Naval Oceanographic Office in 1997 to investigate their applicability to unclassified oceanographic surveying, and a follow-on version, denoted “Seahorse,” was developed subsequently by NAVOCEANO in collaboration with the Pennsylvania State University.



Woods Hole’s REMUS vehicles are small and light



In another “AUV Fest” experiment, one of

enough to be man-launched and recovered from a rubber boat, as shown in this scene from one of the ONR-sponsored "AUV Fests" organized by the Naval Oceanographic Office. Strap-on pods for the side-scan sonar transducers are visible to port and starboard.

Florida Atlantic University's "Ocean Explorer" vehicles goes over the side. Approximately 10 feet long and less than 1,000 pounds, these vehicles are fitted with a dual-frequency side-scan sonar and a long-baseline navigation transceiver. They are also capable of homing on and mating with a docking cone.

Although the original DARPA vehicles were powered by lithium batteries, the Seahorse variant is powered by banks of alkaline D-cells and has demonstrated a mission range of 300 nautical miles – equivalent to 72-hour endurance at somewhat less than its maximum speed of six knots. It carries a variety of instruments for bottom mapping and *in situ* oceanographic measurements and has been successfully deployed and retrieved using a "launch cocoon" on the fantail of typical military survey ships. In an ongoing demonstration project, scheduled for completion next year, Seahorse will be launched and recovered from a simulated SSGN missile tube, to show that large-scale UUVs can indeed be operated from converted SSBNs.

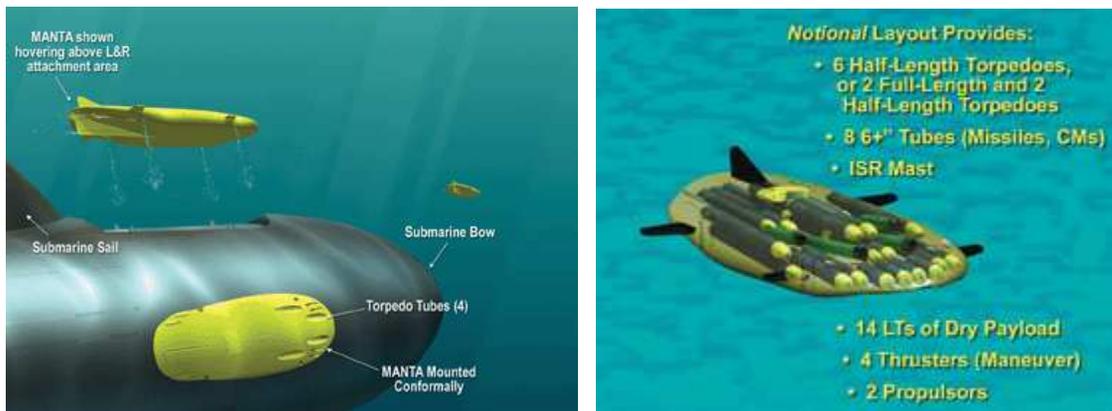
As noted above, the first UUV likely to be deployed operationally in the Submarine Force is the Long Term Mine Reconnaissance System (LMRS) now under development by Boeing Corporation for an Initial Operational Capability (IOC) in FY 2005. Roughly the size of a submarine heavyweight torpedo, LMRS will be 21 inches in diameter and is intended for torpedo-tube launch and recovery from attack submarines. Its primary mission will be autonomous mine reconnaissance, and the vehicle will be equipped with both forward-looking search sonars and side-looking classification sonars for that purpose. In operation, LMRS would be pre-programmed to search potentially hostile areas out to as much as 120 nautical miles ahead of the host submarine. Powered by

lithium thionyl chloride batteries, LMRS is expected to have a top speed of seven knots and a nominal endurance of 40 hours. This should provide an area coverage rate of from 35 to 50 square nautical miles per day. The host submarine will be able to establish acoustic communications with the vehicle at short ranges, and a satellite link will be used to maintain sporadic contact for both command/control and data exchange at greater distances. Pre-planned product improvements under development for the vehicle include precision underwater mapping capabilities and more cost-effective, rechargeable energy sources. In this context, the Office of Naval Research is sponsoring the development of a slow-speed synthetic aperture sonar to improve the onboard classification capability of the UUV with higher spatial resolution, while simultaneously extending the swath width to complement the capabilities of the forward-looking sonar. Also, a laser line-scan imaging device that will facilitate more accurate classification of objects and features detected on the bottom is in consideration.

Already in planning as a more capable follow-on to LMRS is the Mission Reconfigurable UUV (MRUUV). MRUUV will be fielded in two "flights." The first of these will again be a 21-inch diameter, torpedo-tube-launched vehicle, which will build heavily on the lessons learned from LMRS and incorporate a wide range of advanced, modular payloads that may include sensors for electro-magnetic and electro-optical ISR, tactical oceanography, and remote ASW tracking. Northrop Grumman Oceanic Systems, for example, is developing a retractable "ISR mast" that could be raised above the sea surface to conduct optical or electronic surveillance. This will include an already-tested "immersive video" camera with hemispheric coverage and the ability to focus on targets of interest, as well as a multi-band antenna system and corresponding signal processing for collecting both signals and electronic intelligence. Similar collection modules can be added as well for recording acoustic intelligence or detecting biological or chemical warfare threats in both air and water.

The first version of MRUUV will likely appear in FY 2009. Flight two is intended to be a larger-diameter vehicle compatible with the forthcoming SSGN conversions, Virginia-class SSNs with the advanced sail configuration, and possibly surface ships. These

larger vehicles – still notional – will feature more energy storage and payload capacity for both longer endurance and perhaps the ability to launch smaller UUVs or drone aircraft of their own to extend the reach of the onboard sensors. MRUUV's flight two would likely be fielded at the end of the decade.



In the notional MANTA concept developed by the Naval Undersea Warfare Center, several very large, flatfish-shaped UUVs mated externally to a “mother” submarine could provide a powerful and flexible adjunct to the combat power of their host in offboard operations. As shown in the cutaway view of one variant (right), each MANTA vehicle would carry significant payloads of both sensors and heavyweight weapons.

## Future Concepts – Large and Small

As noted, LMRS and the first flight of the MRUUV will be the roughly the size of a 21-inch torpedo, but the large-diameter MRUUV follow-on will represent a quantum leap in size. Futuristic concepts, such as Naval Undersea Warfare Center's MANTA vehicle, would approach, or even exceed, the dimensions of today's Advanced SEAL Delivery System (ASDS) – 65 feet long and 55 tons. Vehicles of that dimension could carry a variety of full-scale weapons – conceptually, MANTA could launch heavyweight torpedoes and – depending on future rules of engagement – might even be unleashed to wield lethal force against enemy ships, submarines, and shore installations.

If actually developed, MANTA would introduce revolutionary new concepts of submarine operations – and require corresponding changes in submarine design. Envisioned as large, somewhat ray-shaped vehicles as much as 50 feet long, four MANTAs might be carried externally on future submarines by integrating them

conformally into launch-and-recovery sites just behind the bow. With the ability to replenish their energy sources onboard and to change out the MANTAs' modular mission packages as needed, the host submarine would gain extraordinary combat power, reach, and flexibility. Moreover, the MANTA payloads of torpedoes and other weapons would be available to the host as additional onboard resources as long as the UUVs remained attached. NUWC has already tested at sea a one-third scale MANTA prototype capable of carrying multiple Mk 48 torpedoes, and they have also demonstrated its ability to launch smaller UUVs while underway. MANTA remains an ambitious concept in the early stages of research and development, and implementing a MANTA-like vision for future submarine warfare would require at least a concerted, decade-long effort.

There are several interesting exceptions to the trend toward larger UUVs for naval warfare applications. Naval Special Warfare (NSW) forces have a requirement for performing shallow-water reconnaissance in support of amphibious landings and hydrographic mapping. These covert operations would be carried out from small craft in coastal waters, and a small UUV – denoted the Semi-Autonomous Hydrographic Reconnaissance Vehicle (SAHRV) – has been identified as a leading solution. Woods Hole has already implemented a successful concept demonstration using a derivative of their REMUS vehicle, mounting both a side-scan sonar and a down-looking laser Doppler velocimeter for both navigation and current measurements. An inventory of 28 vehicles is planned, and several production contracts have already been awarded. Similarly, the MIT Beneath the Wave of the Future (continued from page 24) organization that developed Odyssey has designed for Lockheed Martin a mine-countermeasures AUV called CETUS in a flatfish-shaped envelope only six feet long and weighing just 330 pounds, including sensors. This low-cost system uses lead-acid batteries for propulsion and differential thrust for control to achieve ranges of 15 to 25 miles. Like REMUS, CETUS has also been “shown” at recent ONR/NAVOCEANO “AUV Fests.” Also of interest are bottom-crawling vehicles that mimic the locomotion of crabs or lobsters – especially useful in the surf zone – and futuristic UUVs that propel themselves using flexible structures that imitate the fin and body motions of fish for greater

efficiency.

Navy-sponsored researchers have been investigating the potential for integrating multiple, small UUVs – and an associated underwater support infrastructure – into a comprehensive distributed surveillance system denoted the “Autonomous Ocean Sampling Network” (AOSN). AOSN would consist of a substantial number of independent, but mutually communicating, UUVs equipped with tactical and/or oceanographic sensors for continually searching a shared ocean volume. Using underwater docking stations and surface communication buoys spaced periodically in the ocean volume of interest, participants could dump collected data, replenish power sources, and update mission assignments. Virtually all of the sensor, propulsion, and docking technology needed to implement such a scheme is already in hand, but challenges remain in devising a reliable methodology for “autonomous collaboration” among the vehicles.

### **Recurring Technical Shortfalls**

Accelerating progress in the realm of electronic computation and control, data processing, information management – and the packaging of these functions into smaller and more energy-efficient components – have led directly to the growing list of impressive UUV capabilities described above. The potential for further growth is apparent. Nonetheless, three major technical challenges remain: energy storage, in situ communications, and autonomous control.

Essentially all state-of-the-art UUVs today are battery-powered, and battery capacity remains the most fundamental limitation on range and endurance. Despite continuing efficiency improvements and increases in the energy density of both conventional cells and more recent electrochemical alternatives, no quantum breakthrough has been found in energy storage that would permit relatively small UUVs to perform theater-scale missions or long-duration trailing tasks. Since the power required to propel an underwater vehicle is roughly proportional to its surface area – and stored energy capacity to its volume – the mission duration (or range) achievable at given velocity can be shown to vary directly with vehicle dimension, characterized by length or diameter – i.e. twice the duration, twice the size. This is a key factor in explaining the

increasing physical scale of extended-range UUVs planned for the future. The same hydrodynamic laws also predict that the required propulsive power varies with the cube of vehicle speed, which drives another cruel trade-off and explains why so many of today's UUV missions are executed at less than five knots.

For the many useful military and naval missions that do not require long endurance – limited-area surveys or reconnaissance over short distances; repetitive patrols in scenarios where periodic energy replenishment is tactically feasible; and in peacetime oceanographic characterization – small UUVs will remain attractive for their low-cost, efficiency, ease of handling, and quick turn-around. Additionally, several futurists have suggested “staging” concepts in which large, forward-deployed UUVs would launch smaller, perhaps expendable, UUVs of their own, both as a force-multiplier and for access to hostile areas inaccessible to larger, even unmanned, platforms.

Communications remain a problem area, particularly to and from underwater vehicles at depth. Despite the availability of undersea acoustic communication techniques in which “channel-matching” and intensive digital signal processing are used to sort out multi-path interference in shallow water, effective data rates will likely be limited to no more than several tens of kilobits per second over distances of several tens of miles. This is an impressive achievement, and it has already been put to use in some of the more limited scenarios described immediately above, particularly when covertness is not an issue. Additionally, short-range acoustic communications have already been demonstrated for exchanging data and command information among nearby vehicles and docking stations, or when operating close to manned host platforms. But because so much of the data that prospective long-range missions are intended to collect will be inherently high-bandwidth – imagery, electronic or communications intelligence, detailed bottom surveys – there seems no real alternative to recording the “take” on board for post-mission playback – or devising some means to relay it back to the user by satellite or other means. One promising alternative is the so-called “COMNAVAID” approach, in which ocean areas of interest would be seeded with multiple surface buoys in contact with both GPS and

communication satellites and used as relays for nearby UUVs. Relatively short-range two-way acoustic data links would establish connectivity between vehicles and buoys for both data and command/control. This technique follows directly from the network-centric orientation now gaining ground in the Navy.

Even in today's relatively limited missions, reliable autonomous control remains a significant risk factor. Despite a growing capability for two-way communication with deployed UUVs, the vehicles must still be "smart" enough to decide how to react to unforeseen circumstances between communication sessions and either take appropriate action or recognize the need to contact home base for instructions. A number of tools are available here – artificial intelligence, "fuzzy" logic – but as the range and sophistication of UUV missions increase, maintaining sufficient vehicle autonomy may become the most limiting factor in implementing any future vision.

### **An Accelerating Sea-Change**

After nearly three decades of development and experimentation – much of it supported by the Navy – unmanned underwater vehicles are close to joining the fleet in meaningful numbers and substantive roles. Because their communication and command/control issues have been so much easier to resolve, unmanned *aerial* vehicles (UAVs) have been proving their value in combat for over ten years. For UUVs – out of sight and often out of touch in the depths of the ocean, these problems remain formidable. But the winds are shifting; a sea-change is imminent. With an active and enthusiastic development community, a powerful legacy of demonstrated technologies, increasing industry acceptance, current interest in Special Forces applications, and the approaching deployment of LMRS by the Submarine Force, UUV's are rapidly gathering momentum and a critical mass of supporters. The technologists have delivered, and there is no lack of imagination in proposing future concepts of operation. But what makes these times especially exciting is the real possibility that implementation is now only a matter of time.

Dr. Whitman, UNDERSEA WARFARE's Senior Editor, worked recurrently with underwater weapons and UUVs for much of his 38-year Navy civilian career.

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