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A REVIEW OF THE APPLICATION OF UUV TECHNOLOGY TO MINE COUNTERMEASURES

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A review of the applicability of UUV technology to mine countermeasures

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Executive Summary:

The drive to reduce defence expenditure has resulted in significant changes to defence research and development goals. A critical difference in naval strategy is the emphasis on the need for naval forces to operate in shallow water. The proliferation of low cost mines available to potentially hostile countries together with high exercise costs and risks related to the operation of present NATO MCM units require the development of Unmanned Underwater Vehicles (UUV) capable of performing a variety of operational missions. UUV may be Autonomous (AUV), or remotely operated (ROV).

UUV can execute a variety of military roles due to their capability to achieve significant threat reduction when used in shallow water scenarios. Specific roles, such as providing support to amphibious landings, involve many forms of mission, which can conveniently be grouped under three headings: mine countermeasures, offboard sensor deployment and military oceanography.

This paper reviews UUV technology in the context of MCM and shows that UUV have reached a sufficient level of development to be considered as candidate systems for future MCM operations. AUV in particular, have the potential to effectively perform missions, which would not be possible except at high risk to conventional assets. The rapid development of technology will overcome remaining limitations by the first decade of the next millennium when AUV will be an essential part of modern MCM systems.

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A review of the applicability of UUV technology to mine countermeasures

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Abstract:.

The emphasis on littoral warfare, the proliferation of low cost mines available to potentially hostile countries, high exercise costs and risks related to the operation of present NATO MCM units, require the development of Unmanned Underwater Vehicles (UUV) capable of performing a variety of operational missions. UUV may be Autonomous (AUV), or remotely operated (ROV).

The scope of this paper is to review UUV technology in the context of MCM. The operational aspects of future MCM are briefly addressed and a broad operational requirement for UUV is proposed. Underwater vehicles relevant to MCM are examined together with some of the military and scientific programs being undertaken in the different NATO nations. UUV technology is discussed and the performance that is likely to be achieved in the near future is outlined.

UUV concepts of operation are technology limited in four important areas: navigation accuracy, communication bandwidth, robust autonomous mission control functionality and power system energy densities. Current advances in navigation are encouraging and good progress is being made in the development of compact effective navigation systems and in map based navigation techniques. Limitations in communication capabilities are being addressed by the use of fibre optic data links and by research into maximizing acoustic communication bandwidth and into advanced data compression techniques. The unfavourable underwater channel will however prevent high data rate acoustic transmission of information. High capacity, low cost data storage allows to complete some UUV missions without the need for on-line communication. The issue of achieving robust autonomous control for UUV is intimately connected with progress in UUV sensor technology. Recent developments have seen the fielding of intelligent navigation, guidance and control systems and intelligent on-line mission planning systems. The high cost of high energy density power systems is however limiting the realization of the more advanced UUV system concepts.

The review shows that UUV have reached a sufficient level of development to be considered as candidates for future MCM operations. AUV in particular, have the potential to effectively perform missions which would not be possible, except at high risk, with present MCM assets. The rapid development of technology will overcome remaining limitations by the first decade of the next millennium when AUV will be an essential part of modern MCM systems.

Keywords: UUV, AUV, MCM

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1
Introduction

The emergency of a new world order following the break-up of the former Soviet Union and the drive to reduce defence expenditures, have resulted in significant changes to the defence sector research and development goals. A critical difference in naval strategy has been the new emphasis on the need for naval forces to fight and survive in shallow, confined water areas, rather than in deep waters where previously the threat was likely to arise. The proliferation of low cost mines available to potentially hostile countries together with the high exercise costs and risks related to the operation of present NATO MCM units require the development of unmanned underwater vehicles capable of performing a variety of operational missions. In the literature these are known as UUV and comprise the truly Autonomous Underwater Vehicles (AUV) and the Remotely Operated Vehicles (ROV) that are remotely controlled by a human operator.

The oil exploration industry has obtained remarkable results in building and controlling complex underwater structures by means of increasingly powerful and capable ROV. The defence sector has focused on the research and development of advanced AUV and their subsystem technologies. The primary reason why advanced UUV are considered as candidate systems for executing a variety of military roles is their potential for achieving significant threat reduction when used in shallow water scenarios [1]. Specific roles, such as providing support to amphibious landings, involve many forms of missions that can be implemented by UUV, including intelligence gathering, reconnaissance, mine detection, classification and disposal. Possible roles and tasks for naval UUV can be grouped under three headings: mine countermeasures, offboard sensor deployment and military oceanography. To optimize vehicle effectiveness in such missions, UUV should be considered as integrated elements of a task force [2] and their design criteria should include additional constraints which depend on the vehicle's relationship with the host platform (e.g. surface ship, submarine, vehicle handling system, launch and recovery, etc.) and remote facilities (e.g. command and control systems, communication links, navigation systems, mine warfare databases, etc.).

Although the focus of this paper is on the use of UUV for MCM applications, some of the most interesting sensor deployments are those associated with the use of UUV within rapid environmental assessment (REA) scenarios. Although an evolving operational concept, REA has many similarities to currently planned civil underwater survey missions and some of the key technology aspects are being demonstrated in current scientific UUV programs. UUV complement existing data gathering system, by providing, for example, the spatial coverage lacking in a moored station; the ability to carry comprehensive, multidisciplinary sensor payloads, exceeding the capacity of sub-surface floats; the 'intelligence' to navigate over controlled tracks; and the diving capability to provide subsurface information to augment satellite-derived surface fields.

UUV concepts of operation are technology limited in four important areas: navigation accuracy, communication bandwidth, robust autonomous mission control functionality and power system energy densities. Advances in navigation capability are encouraging and good progress is being made in the development of compact effective navigation systems, robust UUV DGPS reception systems and in bathymetric and geophysical map based navigation techniques. Limitations in communication capabilities are being addressed by the use of fibre optic data links and by research into maximizing acoustic communication bandwidth and into advanced data compression techniques. The unfavourable underwater channel will however prevent high data rate acoustic transmission of information and a possible alternative is the use of radio frequency links when vehicles are on the surface. The availability of very high capacity, low cost data storage allows to complete some UUV missions without the need for high bandwidth on-line communication. The issue of achieving robust autonomous control for UUV is intimately connected with progress in UUV sensor technology, sensor data processing and intelligent system research more generally. Recent developments have seen the fielding of intelligent navigation, guidance and control systems and intelligent on-line mission planning systems. However autonomous control is for the moment insufficient to perform most military operations. Perhaps the most fundamental limitations on realizing the more advanced UUV system concept are the high cost and limited availability of high energy density power systems.

UUV have evolved from engineering curiosities to practical vehicles used in experimental demonstrations of operational and scientific utility. The scope of this paper is to review the state of the art of UUV technology applicable to MCM. Section two addresses some operational aspects of future MCM and outlines tentative broad operational requirements for UUV. Section three describes underwater vehicles relevant to MCM, reviewing present systems and some military and scientific programmes. Section four focuses on UUV platforms. Section five discusses the technology available and outlines anticipated performance. Section six summarizes the findings.

2
Operational Considerations

Mines are among the cheapest and most effective devices employed in sea warfare and the possibility of laying them from surface vessels, from submarines or from the air amplifies their threat. When used for defensive purposes they generally serve to protect coastal areas against hostile intrusion; when laid for offensive purposes they serve to interrupt maritime supply routes or to prevent the use of harbour facilities. Depending on the tactical objective and type of construction they can be laid in all depth ranges from the surf zone down to several hundreds of metres. Detonation systems use a combination of acoustic, magnetic and pressure sensors to detect the signature of a passing vessel and appropriate detection criteria to trigger the explosion. Although modern mines can be highly sophisticated, also very simple and old mines with physical contact fuses can still pose a very considerable threat as demonstrated in the Gulf War. The size, shape and material of modern mines make their detection and neutralization difficult; furthermore, when mines are buried in the bottom sediments, either by natural processes, or by self burying devices, they become virtually undetectable by existing sonars.

The mine countermeasure systems used to detect and destroy mines are sophisticated and expensive. In general they are acoustically quiet, surface vessels of non magnetic design which serve as platform for hull mounted or variable depth detection sonars, equipped with cable guided ROV for mine identification and neutralization. The final decision as to whether a mine-like object detected by the sonar is a mine or a non-mine, is by a human operator. Reliable detection of modern mines, including buried mines, higher safety for ships and their crews and improved area search are essential features of new mine countermeasure systems. Mine countermeasure forces are increasingly likely to be involved in regional conflicts and peace keeping operations in littoral waters in support of amphibious landings. As a consequence, in addition to the general requirements listed above, future systems should be capable of supporting clandestine or low-visibility operations in very shallow water or in the surf zone.

The threat from current and future advanced mines requires an increased offboard sensing capability and the achievement of greater stand-off distances: UUV have the technical potential to meet the new operational requirements and in some cases, they offer the only way ahead to realize new mine countermeasures capabilities. The key advantages of UUV are their ability to operate stealthily in areas where major assets cannot go (or where they might be exposed to unduly high threat levels) and their ability to act as remote sensors to collect information. Despite potential defence applications for UUV and a number of UUV research and development programmes, the USA is the only country known to have an operational requirement at present [1]; their concept of operations and the possible applications for UUV are summarized in the next subsection.

2.1 US Navy MCM concept of operations

The growing importance of littoral warfare has significant implications for the manner in which the US Navy approaches the mine countermeasures problem. Sea mines are perhaps the single most attractive weapon available to third world nations for the purpose of preventing naval forces from accomplishing their objectives in the littoral environment. To deal with this threat in the future, the US Navy has formulated a new operational concept for mine countermeasures. A central feature of this revised concept of operations is the integration of mine countermeasures with the main war-fighting capabilities of the Navy. The recently promulgated Mine Countermeasures Concept of Operations[1] is a synergistic mix of four focused operations that build upon each other to provide to naval forces the capability to counter the mine threat (Figure 1).

Figure 1 *Concept of Operations for the US Navy*

The four mine countermeasures operations which compose this concept of operations are:

- Survey, Mapping and Intelligence Operations
- Surveillance Operations
- Organic Mine Countermeasure Operations
- Dedicated Mine Countermeasure Operations

Briefly, this top-level Concept of Operations for Mine Countermeasures can be described as follows:

Mine countermeasures operations begin during peacetime with actions to *gather relevant environmental data and intelligence information* on the mining capabilities of potential adversaries. As tensions increase, focused *surveillance operations* provide updates to databases developed during peacetime. As tensions escalate, during the initial efforts to

[1] http://www.ncsc.navy.mil/CSS/Papers/conceptofoperations.htm

shape the battle space, naval forces utilize *organic mine countermeasure* capabilities to accurately assess the risks associated with operating in mined waters, or avoid mined waters altogether. Organic mine countermeasures operations will also serve to focus the efforts of *dedicated mine countermeasure* forces to clear enemy mines to support the projection of power from the sea. The dedicated mine countermeasure forces may be required to effect the enlargement of the overall naval scenario as necessary to permit follow-on operations.

Based on this operational concept, the US Navy is actively pursuing UUV based MCM applications: the Remote Minehunting System (RMS) and the Near-term Mine Reconnaissance system (NMRS) are under development. The long-term mine reconnaissance system (LMRS) is currently the subject of design studies and has a planned build date of 2002. These systems are described in the next section.

2.2 Operational Scenarios

The operational use of UUV has been addressed in an early work by Riffenburg [3] that identified seventeen different missions covering the naval tasks of surveillance, reconnaissance, environmental data gathering, mine avoidance, jamming and weapon delivery. More recently Hornfeld and Leicht analyzed in detail two examples of UUV applications, the clearance of an anchorage area in coastal vicinity and the reconnaisance of a subsea route for a submarine transit through a mined strait [4].

In general, the situations where UUV will improve MCM missions can be categorized as follows:

- The performance of available systems is insufficient to counter the threat
- The risk and/or the effort for traditional platforms and their crew is too high compared to the achievable results
- The mission has to be clandestine.

In particular the ability of UUV to manoeuver in very shallow water, virtually undetected, together with the possibility to enter mine fields without exposing human operators to undue risks, will significantly increase current MCM capabilities.

With reference to the NATO terminology, UUV can be utilized in *exploratory* missions, where it is necessary to verify the presence and the type of mine fields, or in *reconnaissance* missions, that is the delimitation of areas free of mines for amphibious landings or ship transit, or in *minehunting* missions to accurately localize mines for subsequent clearance[2]. In peace time they can considerably reduce the costs of conducting *route surveys,* to routinely control that sea-lanes of operational interest are free of mines. These missions have wide ranging requirements, but they have a common goal to clear a channel that is hundreds of kilometres long and hundreds of metres wide.

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[2] UUV cover the *clearance* role with the utilization of specialized mine killer subsystems

2.2.1 The threat

The threat the UUV will have to counter is the sea mine in defence of surface units or submarines in the areas of interest. The possible targets encountered are listed below, subdivided by water depth, according to the usual MCM definitions:

Surf Zone (0-4m): Obstacles and anti-landing weapons, detonated by contact or magnetic influence, with high probability of burial. Typical bottom mines are not present because their safety arming mechanism prevents firing in the surf zone.

Very shallow water (4-10m): Same weapons as in SZ plus conventional anti-landing bottom mines, with high probability of burial.

Shallow water (10-25m): As before plus anti-ship influence bottom and contact mines moored 2 to 10 m from the surface. Low to medium probability of burial.

Deep water (below 25 m): Anti-ship and anti-submarine mines as before up to 60m. In deeper waters bottom torpedo mines or moored mines can be present 2 to 150 m from the surface. Low probability of burial below 60 m.

Table 1 summarizes the characteristics of typical mines.

Mine type	Shape	Dimensions	Material
Anti-landing mine (bottom mounted)	Truncated cone, truncated pyramid, half sphere	40 cm to 100 cm	Fibreglass or non magnetic metal, 1cm thickness
Moored mine (shallow and medium depth)	Sphere, ellipsoid for the mine, cylinder or cube for ballast	Mine 1 m ϕ Ballast 1 m ϕ	Fibreglass or magnetic metals, less than 1 cm thick, 2/3 full with air
Bottom mine	Cylinder with rounded endcaps	1 to 2.5 m long, 50 cm diameter	Fibreglass or non magnetic metal 1 cm thick
Moored mine (deep water, with torpedo)	Cylinder in vertical position	1.5 to 3m long	Magnetic metal, 1 to 2 cm thick

Table 1 *General characteristics of mines*

2.3 Operational requirement

Considering the various missions that an UUV could perform, the type of threat likely to be encountered and the environment where the mission will be carried out, an example of operational requirement for a multi-role UUV for MCM could be outlined as follows[3]:

[3] This list of requirements is derived from an internal document of the Italian Navy by Edoardo Di Gennaro, *UUV per esplorazioni in acque pericolose*, Rome 12th May 1997.

- Autonomous navigation on the sea surface and to a depth of 300 m following programmed tracks, with anti collision capability sufficient to avoid large obstacles and rapid changes of the bathymetry

- Sensor suite to perform the required detection and identification tasks: including a combination of collision detection high frequency sonar, side scan sonar and magnetic sensors for mine detection, optical and very high frequency acoustics sensors for identification.

- Stability as required by the detection and identification sensors.

- Speed variable from zero (hovering) to 7 kn, cruise speed of 4 kn.

- Area covered at 4 kn cruise speed in detection mode greater than 4 km^2/h against bottom targets and greater than 6 km^2/h against volume targets.

- Target relocation capability better than 10 m in absolute and relative coordinates.

- Autonomy up to 200 km from launching platform.

- Physical dimensions and weight such to allow easy deployment from surface units in sea state 4 conditions and from submarines *via* torpedo tubes[4].

- Limited magnetic and acoustic signature to minimize risk of activating influence mines.

- Modular construction allowing trade off of endurance and sensor suite complexity for a variety of missions.

- Limited reconfiguration time between missions (few hours).

In addition, the units that are completely autonomous and do not have a data link to the mother ship should be capable of quickly downloading the data acquired during the mission (few minutes).

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[4] This may however place unnecessary constraints on the dimensions of the control surfaces and may reduce the manoeuverability of the UUV at low speed.

3
UUV for MCM:present situation and current developments

Unmanned underwater vehicles have been under development by the military and civilian research communities for a number of years. Significant progress has been made and major projects underway in several countries are now at the stage of demonstrating missions of real utility. This section reviews the status of MCM programmes that utilize underwater vehicles.

3.1 Present Systems

Underwater vehicles currently used in MCM systems can be grouped in two categories: cable guided ROV, including Propelled Variable Depth Sonars (PVDS) and expandable mine disposal systems

3.1.1 Cable-guided ROV

Cable-guided ROV are used for identification and possible neutralization of objects classified as mines. They are used to position a mine disposal charge at the mine. During this process, the minehunter stays at a safe distance from the mine. The ROV is guided to the mine with the aid of the sonar. For final identification of the mine and precise final approach, the bow section of the ROV is equipped with a high-resolution close-range sonar and a TV camera. A widely adopted mine disposal vehicle is the PAP produced by the French company ECA; the latest version of this ROV is designated MARK 5. Adapted by major Navies (UK, Singapore and Japan), this vehicle allows mid-water identification (with vertical thrusters), strong current operating range (up to 3 kn current), diversity of sensors (2 video cameras and 1 sonar) through a fibre optic transmission link. Replaceable, rechargeable batteries are provided for propulsion and electrical supply of the PAP MARK 5. The vehicle has a maximum speed of 6 kt and the maximum operational depth is 300 m.

The German Navy opted for the mine disposal vehicle *PINGUIN B3* of STN ATLAS Elektronik for the MJ 332 minehunters. This larger and heavier vehicle has higher power reserves, a speed of 8 kn and can be automatically guided to the mine *via* the automatic control system. It is capable of carrying two mine disposal charges. The cable connection consists of a towed, re-usable fibre optic cable. Control surfaces and a lifter motor integrated in the fuselage give the vehicle high manoeuverability at all depths. The maximum operational depth is 200 m.

The Propelled Variable Depth Sonar (PVDS) minehunting configuration is also a promising concept. The idea is to integrate the sonar arrays and electronics on board a self propelled underwater vehicle and to steer it ahead of the ship and underneath the thermocline layer. This assures the absolute safety of the ship by locating the sonar ahead of the ship and not under the ship as in a Variable Depth Sonar (VDS). Example of this concept are the *Bofors Double Eagle*[5] and the upgraded PAP developed by ECA and STN ATLAS Elektronik. A typical Mine Countermeasure installation could consist of two *Double Eagle* ROV. The first equipped with a mine hunting sonar (such as the Thomson-Marconi TSM-2022 MK 3) and the second Mine Disposal *Double Eagle* (MDS) equipped to place a charge within a few centimetres of the mine. After the recovery of the ROV the mine clearance charge would be remotely detonated causing the sympathetic detonation of the mine.

3.1.2 Expendable mine disposal systems

As visual inspection is the usual method of mine verification, the optimum approach is to take a camera as close to the mine as possible. However, this increases the chance of accidentally triggering the mine. The concept of a cheap disposable weapon overcomes this problem if the mine explodes accidentally, as the weapon has achieved its purpose. A highly manoeuverable expendable weapon is an ideal platform for directing a shaped explosive charge through the mine casing and into the explosive material. This has the potential of being more effective against the latest generation of insensitive explosives, where the charge is effectively acting in the same manner as the mine's detonator. It is also more efficient in terms of the size of the charge. Suitable shaped charges contain approximately 2 kg of explosive compared to typically 80 kg in a conventional mine disposal charge. This reduction in the weight and size of the charge in conjunction with new camera technology and the concept of an expendable weapon, makes it possible to manufacture a low cost, lightweight and very effective one shot mine disposal weapon.

Examples of this concept are the *Minesniper*[6] built by Kongsberg Defence & Aerospace AS and the *Shellfish/Archerfish* manufactured by G.E.C.-Marconi

The *Minesniper* is a lightweight, low cost, mine disposal system, utilising an expendable ROV-type weapon for rapid and efficient mine verification and destruction. It is designed to be effective against bottom mines as well as moored mines in shallow to deep waters. The weapon is also viable for combating drifting mines. Several features have been incorporated into the system to achieve rapid mine clearance. Mission times of 15 minutes at 500 m target range may be obtained. The weapon is guided towards the target by use of the mine countermeasure sonar. A specific acoustic transponder ensures that the weapon is clearly visible on the sonar screen, together with the target. Based on the position updates from the sonar, *Minesniper* will bring the weapon automatically to the target, where the operator will take manual control to perform inspection and destruction. Short range location of the mines is achieved through the use of a homing multibeam sonar fitted to the weapon. The weapon also carries a camera for visual inspection and verification, together with a shaped charge warhead for detonation of the mine. Alternative warheads may be included. Communication with the weapon is through an optical fibre. The weapon is energy autonomous with a 1 h rated endurance. Maximum travelled distance at normal speed is 4000 m. The weight of the weapon is approximately 25 kg, when rated for 500 m depth.

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[5] http://www.naval-technology.com/contractors/mine_disposal/bofor_eagle/

[6] http://www.naval-technology.com/contractors/mine_disposal/kongsberg/index.html

Archerfish is a small expendable vehicle (1 m length, 200 mm ϕ) which is remotely guided onto the mine target by using a sonar, a TV camera and a fibre optic link. It carries also the explosive warhead. *Shellfish,* derived from *Archerfish* technology, presents some additional features. The strengthened fibre optic umbilical used to transfer commands to the propellers and to receive video images and sonar signals is also used for recovery, its typical mission is 55 operational minutes at a range of 300 m and a recharging time of 10 min. A maximum speed of 7 kn and hovering capabilities without affecting acoustic operations are possible.

3.2 Current Developments

There is a growing international trend towards AUV in the field of MCM equipment. However, the aspect of autonomous operation with the required capabilities such as independent decisions presents a major challenge in terms of system design. A sensible interim step towards the ultimate objective of the AUV currently pursued is the Supervised Underwater Vehicle (SUV) equipped with essential AUV features yet still linked to the surface vessel with a fibre optic cable or with RF communication. The operator thus has the possibility to intervene in SUV missions at any time. Such units offer an excellent platform for testing new subsystems and procedures. A few systems which have reached an advanced stage are described below

3.2.1 Remote Minehunting System (RMS)

The Remote Minehunting System (RMS)[7] is being developed to meet the US requirement for organic mine countermeasures for surface ships. RMS will be an organic, off-board mine reconnaissance system. As part of the advanced forces, surface ships will employ RMS to meet the demand for over-the-horizon mine reconnaissance of anticipated operating areas in support of the ship's individual mission and to prepare for the arrival of other naval forces. The RMS sensor suite will be used against bottom and moored mines for mine reconnaissance in deep water up to a portion of the very shallow water (VSW) region. The remotely operated system, using computer aided detection and precise navigation systems, will detect and classify mines and record their locations for avoidance or subsequent removal. The system, with organic handling, control and logistic support, is designed to be air transportable to forces anywhere in the world. RMS will provide a rapidly deployable mine countermeasures system to surface combatant forces in the absence of deployable mine countermeasures forces. In August 1994, the Remote Minehunting Operational Prototype (RMOP) was completed and integrated the AN/AQS 14 minehunting sonar (on a variable depth winch) and the SEABAT forward looking sonar with the *Dolphin* semi-submersible ROV [5]. Additional follow-on developmental contingencies are being advanced to meet mid-term requirements, including improved vehicle performance and integration in *Spruance* (DD-963)-class destroyers. A suite of advanced sensor technologies[8] for compatible, compact and power-efficient use on the *Dolphin* ROV under development include a deep-water toroidal-volume search sonar (TVSS) for hunting volume mines in deep water; a side-looking

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[7] http://www.ncsc.navy.mil/CSS/Projects/remomine.htm
[8] http://www.ncsc.navy.mil/CSS/projects/actdfact1.htm

sonar (SLS) for the detection of volume and bottom mines in shallow water; a synthetic aperture sonar (SAS) for very shallow water operation; a high-sensitivity superconducting magnetic field gradiometer for mine classification and for detection of buried mines; and an underwater laser line scan (LLS) optical sensor for mine identification and associated signal and image processing. Ultimately, these advanced sensors, integrated into AUV launched from submarines and surface ships, will provide naval forces with an organic minehunting capability.

3.2.2 Near-term Mine Reconnaissance System (NMRS) and Long-term Mine Reconnaissance System (LMRS)

The Near-term Mine Reconnaissance System (NMRS)[9] uses a submarine-launched, unmanned, underwater vehicle that provides minefield reconnaissance in deep to shallow water. The NMRS consists of two reusable UUV, launch and recovery equipment, including a winch and drogues and shipboard control, processing and monitoring equipment. Each UUV is slightly shorter than a MK-48 torpedo and is launched and recovered *via* a standard SSN 688-Class torpedo tube. The UUV contain highly accurate sonar systems that can pinpoint and classify mine-like objects. Batteries provide the power needed to propel the vehicle during its sortie and operate the on-board electronic systems. Vehicle status, position and sonar data are continuously relayed back to the host SSN *via* a fibre-optic cable, thereby allowing continuous monitoring of the vehicle during sortie operations and real-time analysis of data to the SSN from potentially mined waters. The NMRS is due to be transitioned to the US Navy in 1999 and its successor, the Long Term Mine Reconnaissance System (LMRS)[10] is currently the subject of design studies and has a planned build date of 2002. The LMRS is a clandestine mine reconnaissance system that employs UUV that are capable of launch and recovery from SSN 688 and NSSN class submarines. The LMRS will address the limitations of NMRS and provide an early, rapid, accurate means of surveying potential mine fields in support of proposed amphibious operations, other battle group operations and for safe ship transit around mined waters.

3.2.3 Autonomous Ocean Sampling Network (AOSN)

Another development that could be of particular interest to MCM is the Autonomous Ocean Sampling Network (AOSN) [6] and [7], funded by the US Office of Naval Research to map the temporal and spatial gradients of the littoral environment. Although this effort is focused on rapid environmental assessment, the system technologies being addressed are directly applicable to MCM. An AOSN consists of a number of fixed and mobile nodes with desired sensors configured to sample the ocean and survey the sea floor with a specified resolution and precision. The mobile nodes are smart, autonomous underwater vehicles; the fixed nodes are initially moorings, progressively replaced by AUV as technology progresses. The essence of this approach is the deployment of a flexible network of many, low cost lightweight vehicles with reliable navigation and communication instead of relying on a few expensive very sophisticated vehicles such as those mentioned in the previous paragraphs. To achieve a practical system, the AUV must remain within a critical cost-size envelope: the best vehicle for this concept is

[9] http://www.onr.navy.mil/sci%5Ftech/ocean/jcm/nmrs.htm
[10] http://www.boeing.com/defense-space/infoelect/lmrs/

moderate in size and cost with a range exceeding hundreds of km. Compared with larger vehicles, vehicles of this class can be deployed and recovered in rougher seas and off smaller platforms. They are more manoeuverable in confined environment and near the bottom. Higher thrust to mass ratio can be obtained for better control in current or turbulence. Low cost manufacturing techniques can be employed together with modular design to optimize costs. Typical vehicles being addressed by AOSN are *Odyssey, Ocean Explorer, Remus*: each is a mobile instrumentation platform with actuators, sensors and on-board intelligence designed to complete sampling tasks autonomously. They are discussed in more detail in the next section together with the technical issues in control, communication, propulsion and navigation common to future MCM systems.

Figure 2 shows the critical envelope addressed by the AOSN concept and compares the size and cost of candidate vehicles with bigger systems that have been built mainly for military applications.

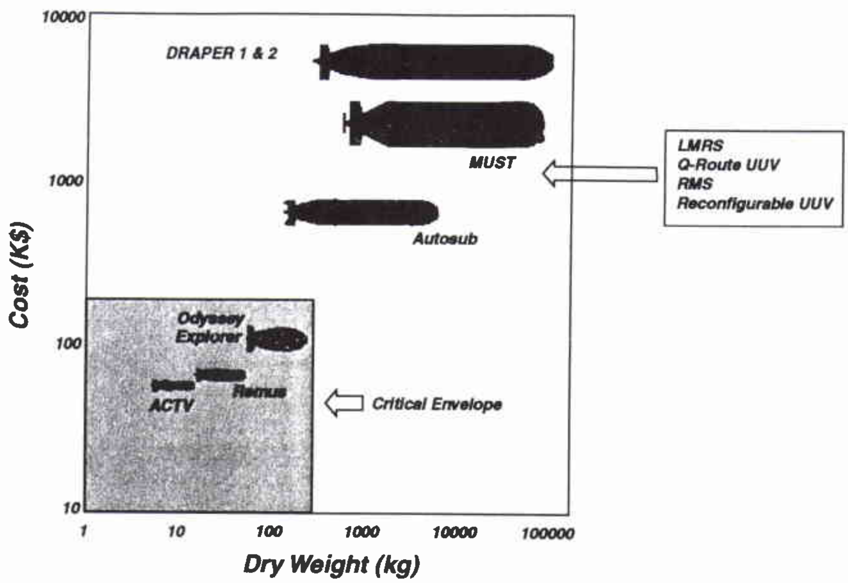


Figure 2 *Comparison of some Autonomous Underwater Vehicles*[11]

Draper 1&2 have been designed and built by Draper laboratory. *MUST* is a large vehicle designed and built by Martin Marietta. Autonomous Conductivity Temperature Vehicle (ACTV) is a modified MK-38 sonar target built by APL/University of Washington for ocean boundary layer measurements in the Arctic. Q-Route UUV is a large vehicle being designed and built by APL/Penn State. Reconfigurable UUV is basically a torpedo (21") size vehicle with interchangeable payloads of environmental sensors. *Autosub* is a multipurpose oceanographic vehicle built by the Southampton Oceanographic Centre. *Remus, Ocean Explorer* and *Odyssey* are described in more detail in the following sections.

[11] The figure is derived from a presentation by Tom Curtin (ONR)

The comparative efficacy of numerous small low-cost units *versus* few greater units was analyzed in the MO-2005 study conclusions [8] and is discussed by Riffenburg in the annex of his paper [9] where he concludes that mini-units are more attractive than mega-units.

The following considerations apply:

- A vehicle cannot grow too large because of logistic limitations in deployment and retrieval operations. A particular constraint is also imposed by the requirement to use torpedo tubes for submarine launch.

- A vehicle cannot grow too expensive otherwise its loss could not be affordable

- A vehicle cannot be too small because otherwise it will be energy limited as its maximum range is proportional to the energy density of the propulsion system and to the volume of the vehicle.

- A vehicle cannot be too small otherwise the affordable payload would not be sufficient to perform adequately its mission

In recent years military, academia and industry developments have converged to medium to small size vehicles: the cost effective envelope seems to have a lower bound of 50 kg and 50 k$ and an upper bound of 1000 kg and 1000 k$.

4
UUV Platforms

This section focuses on the UUV platforms on the market as commercial products, or as the result of national R&D programmes. The platforms are subdivided in three categories: the ROV that receives power and control from a host platform, the Supervised Underwater Vehicle (SUV) that is completely autonomous in terms of propulsion, but is still controlled by a human operator and the truly Autonomous Underwater Vehicle (AUV).

4.1 Remotely Operated Vehicles (ROV)

Notwithstanding diverse dimensions, capabilities and cost, all ROV have the same basic components: the vehicle, the umbilical, sensors and manipulators, control consoles and support platform. The vehicle is the submersible at the end of the umbilical equipped with sensors and manipulators to perform the assigned tasks. Vehicle propulsion is provided by sets of motor-driven propellers which permit the ROV to move precisely while submerged. In general an ROV will have three sets of thrusters allowing vertical, lateral and forward/back movement of the unit. Every vehicle has one or more pressure-proof containers which enclose the control circuitry and the data processing computers. The vehicle is usually protected by a rugged frame that permits easy handling and maintenance, while providing collision protection during operations. The umbilical is the link between the pilot and the vehicle. It provides power and control signals from the host platform to the vehicle and data in the other direction. Traditionally the power and data conductors were wires, but recently there is an increasing use of optical fibre with only the power cable being of copper. The vehicle may be lifted or handled by use of its umbilical, as a strength member is woven into the cable for this purpose. A variety of mechanical arms are available for mounting on all sizes of ROV. These range from simple grabbers to multi-axis units. ROV are usually equipped with still and TV cameras, high frequency sonars and motion sensors which allow the pilot to manoeuver in restricted areas.

All ROV operations require some type of support platform; the ideal is to have highly portable ROV that can use ship of opportunity for surface support. The main limitation of ROV for MCM work is the presence of the umbilical that reduces the range to a few hundred metres from the support platform and affects the manoeuverability of the vehicle. Due to the presence of the umbilical, multi vehicle operations are very difficult due to the risk of entangling the cables. The advantage of ROV is that the operator is always in control and he can take decisions that would otherwise be difficult or impossible for a truly autonomous system (the identification of a mine and the decision to destroy it are tasks which today require human intervention).

As ROV are a mature technology, widely used by industry and military communities, only two examples of vehicles dedicated to MCM are given below.

4.1.1 Deep Ocean Engineering

Deep Ocean Engineering is a major supplier of military ROV for applications such as MCM, ordnance neutralization, object relocation and recovery, maritime-law enforcement, accident investigation, general inspection of hulls and marine structures and installation and maintenance of underwater equipment [10]. Since 1990, DOE has supplied 56 ROV to 11 navies worldwide. They build a flexible and scalable product line that ranges from the general purpose light-weight Phantom 300 to the powerful Phantom Ultimate and comprises more than 15 vehicles of modular design to satisfy the various mission requirements. Table 2 summarizes the characteristics of their MCM platforms.

	Phantom HD2+2	Phantom S4	Phoenix
Weight (kg)	96	118	145
Max depth (m)	300	300	600
Speed (kn)	3	3	> 3
Payload (kg)	9	11	45
Max cable length (m)	640	640	10000
Equipment	TV, Sonar	TV, Sonar	TV, Sonar, Manipulator

Table 2 *Technical data of Deep Ocean Engineering MCM ROV*

4.1.2 Double Eagle

The *Bofors Double Eagle* is a Commercial-Off-The-Shelf (COTS) Mine Countermeasure System (MCM) [11] and [12]. The 1 km tether feeds both power and control signals to the ROV and sonar acoustic and video data back to the ship for processing. The tether allows the vehicle to operate without the weight and size penalties imposed by batteries or other energy storage system. Precise manoeuvering allows this small ROV to place medium sized disposal charges within a few cm of the mine. The ROV is engineered to have no righting moment, allowing accurate positioning without disturbing the target. By careful design the system has almost identical center of buoyancy and center of gravity positions. This allows the craft to be placed in any attitude or position near a mine, in order to optimize identification. The ROV can be configured as a propelled sonar vehicle, or as a mine disposal vehicle. Table 3 summarizes the technical data.

Weight	340 kg
Size	2.1 x 1.3 x 0.5 m (LWH)
Depth	5-350 m (optional 500 m)
Speed (kn)	>6 fwd, 2 astern, 1 lateral, 0.6 vertical
Payload	80 kg, explosive charge; explosive cutter; telescopic arm with charge; sonar and cameras
Launch and Recovery	up to sea state 4
Control	+/- 2 deg (typical) pitch, roll and yaw , Depth +/- 0.2 m
Shipboard Impact	1050 kg and -28 kW power

Table 3 *Technical data of Double Eagle*

4.2 Supervised Underwater Vehicles (SUV)

The limitations imposed by the ROV umbilical, have led to the development of autonomous systems. However, present technology does not yet allow replacement of the human operator. As an intermediate step, a few systems have been designed that are completely autonomous in term of propulsion, but keep a wide-band communication link to the host platform. The communication channel could be an RF link or a free spooling fibre optic tether. The use of fibre optic tether allows retention of the human operator and deferment of technologies that are not yet ready for operational use such as the automated detection, classification and identification of mines. It also overcomes the physical limitations of the underwater acoustic channel that does not allow long-range, high bandwidth communication. The price is of course reduced operational flexibility for fixed tether operations and high costs for over the horizon missions with free-spooling tether. Recent advances in acoustic communication [13] and intelligent buoys [14] allow maintenance of AUV acoustic control over short to medium distances.

4.2.1 Dolphin and ORCA

The *Dolphin* [5] is a semi submersible hull powered by a diesel engine initially designed to provide the Canadian Hydrographic Service with a stable, high speed platform to conduct unmanned surveys in Canada's offshore regions. Three production survey vehicles were delivered in 1986. In 1985, the US Navy ordered two variations of the design for testing with Navy developed payloads. These vehicles are now known as *ORCA's* and are operated by the US Naval Oceanographic Command and the Naval Research Laboratory in Stennis, Mississippi. In 1988, the US Navy ordered two additional *Dolphin* vehicles for development as remote minehunting vehicles. These are now operated by the US Navy Coastal Systems Station at Panama City, Florida and are known as Remote Minehunting Operational Prototypes (RMOPs). In this role the *Dolphin* is equipped with mine hunting sensors, high bandwidth data link and GPS positional receiver. This approach allows the operator to work from a safe distance (up to a line of sight distance of 15 km). As part of the concept, both hull mounted and variable depth sonars are provided so that simultaneous detections can be made on the seabed and in the water column. A tow fish equipped with side scan and forward looking sonars is towed up to 300 m depth at a distance of up to 600 m from the rear of the *Dolphin*. The unit can be deployed either from a craft of opportunity or from a dedicated naval ship and can be transported in one ISO container. The *Dolphin* vehicle specifications are summarized in Table 4.

Length	7.5 m
Diameter	0.99 m
Displacement	3275 kg
Speed	Max 16.5 kn, Cruising 5 kn
Range	620 km at 12 kn
Propulsion	Sabre 212 Hp Turbo-charged Marine diesel
System Control:	*via* UHF narrow band FM full duplex link
Vehicle Control	Motorola 68030 microprocessor
Navigation	Rockwell Differential GPS Sensors

Table 4 *Technical data of Dolphin*

In the minehunting role *Dolphin* has been equipped to carry the Klein 500 single beam sidescan sonar, the AN/AQS 14 sidescan sonar and the Reson 6012 Seabat. *Dolphin* and *ORCA* vehicles in hydrographic service operate the Simrad EM 100 or EM 950 multibeam echo sounders.

4.2.2 XP-21

Raytheon has proposed a multi-mission unmanned underwater vehicle named *XP-21* for hydrographic and mine reconnaissance, intelligence collection, acoustic surveillance and remote mine hunting and avoidance [15]. The self propelled vehicle has the form factor of Mark 48 torpedo, is build in modular sections (5 to 9) to accommodate different payloads and increased volume for energy storage and communicates with the host platform by a fixed or free spooling single mode fibre. The system is designed to carry a wide range of sensors for multimission aplications including multibeam sidescan sonar, forward-looking sonar (Reson SeaBat 9001S) for mine detection and classification, magnetometers and optical sensors such as the Applied Remote Technology LS-4096 laser imaging system. Navigation sensors include Doppler sonar, ring laser gyro Inertial Navigaton Unit (INU) or GPS/ultrashort baseline system *via* the support ship. Onboard power is *via* either lead-acid or silver-zinc batteries. A newly developed alluminum oxide fuel unit providing 10 times the range of lead-acid batteries is also available. Lateral and vertical thrusters enable XP-21 to transit from hull hover to 5 kn. Table 5 summarizes the technical data.

Length	5 - 8.5 M (depending on payload
Diameter	0.533 (Submarine tube compatible)
Displacement (in air)	730 - 909 kg (depending on payload)
Payload	0.1 - 0.75 m^3 (dry) / 0.1 - 0.45 m^3 (wet)
Propulsion	DC brushless thrusters
Speed	5 kn (capable of ROV type hovering)
Operating depth	600 m

Table 5 *XP-21 specifications*

4.3 Autonomous Underwater Vehicles (AUV)

AUV have been under development by the military and research community for a number of years and recently significant progress has been made. Major projects in several countries have demonstrated missions of real utility, for example: the survey of coastal front in Hero Strait [16] and the measurement of 3-D scattering from buried targets in very shallow water [17] by the MIT *Odyssey II*, the laying of 175 km cable under the ice by ISE Research *Theseus* [18], the swath bathymetry survey of Oslo fjord by *HUGIN* [19], [20] and the acoustic sea floor mapping off Florida by the Florida Atlantic University (FAU) Ocean Explorer [21]. Other vehicles are under development in Europe such as *Autosub-1* [22] at SOC and *MARTIN* [23] in Denmark.

The first generation of vehicles had flooded fairing, wet cabling and internal pressure vessel (MIT *Odyssey*, FAU *Ocean Voyager*), but as payload and navigational elements are interleaved, mechanical reconfiguration is time consuming. This problem was addressed and solved by the modular design of the FAU *Ocean Explorer*, which separates payload from navigation section, enabling field reconfigurable mission packages. The latest development[12] is the modular multi purpose design of the FAU mini UUV, which combines modular sections of pressure vessel as hull with flooded partial fairings. This approach, which allows economies of scale over a range of missions, seems quite promising.

AUV can be divided in three categories:

- ***Large UUV***: 21" and larger diameter, >5 m long, >1000 kg, require large support vessel for launch and recovery and engineering team for maintenance (e.g. *Theseus*, *Autosub*)

- ***Medium UUV***: 0.5m diameter, 2 to 5m long, 100 to 1000 kg, (MIT *Odyssey*, FAU *Ocean Explorer, Hugin*) requires small support vessel

[12] The mini AUV is being tested and will become available during the course of 1999

- ***Mini UUV***: 0.25 m diameter, 1 to 2 m long, 30 to 100 kg, modular construction (*Proteus, Remus, MRMRS*) requires small boat.

Examples of each category are presented below. For a comprehensive list of AUV developments see [24] and the web URL *www.acim.usl.edu/~maja/AUV/AUV-list.html*

4.3.1 Theseus

Over the past five years, International Submarine Engineering Research and the Defence Research Establishment Atlantic have developed a large autonomous underwater vehicle, named *Theseus*, for laying optical fibre cables in ice-covered waters [18]. In trials and missions conducted in 1996, this vehicle laid a fibre-optic cable in a completely autonomous mode for a distance of 200 km under Arctic sea-ice and then returned to the launch station for recovery. It demonstrated a navigational error of less than 0.5% of the distance travelled and cross-track error was reducible to 0.05%. *Theseus* operates in either depth-keeping mode or bottom-following mode, up to maximum depth of 1000 m. The vehicle is equipped with an inertial navigation unit and Doppler sonar speed sensor for autonomous navigation, a forward-looking obstacle avoidance sonar, an acoustic homing system and acoustic transponders for use with surface tracking stations. An acoustic telemetry system enables communication with *Theseus* from surface stations and an optical telemetry system is used for system monitoring while *Theseus* is laying optical fibre cable. All sub-systems are controlled by an MC68030 based sensor integration and control computer. Although the vehicle is currently configured for cable laying, other missions could be accommodated with minor changes to the payload section of the vehicle. *Theseus'* qualities of covertness, long endurance and precise navigation make possible such tasks as oceanographic data collection, remote route surveys, remote mine hunting, the rapid deployment of acoustic and non-acoustic surveillance systems and even the towing of mobile sensor arrays. Longer missions could be accommodated by replacing the current silver-zinc batteries with fuel cells or other AIP (Air Independent Propulsion) power plants. Table 6 summarizes the main vehicle characteristics

Length	10.7 m
Diameter	1.27 m
Displacement	8600 kg
Speed	4 kn
Range	700 km
Propulsion	6 Hp brushless DC motor
Power	360 kWh Silver Zinc Battery

Table 6 *Technical data of Theseus*

4.3.2 Hugin

Hugin is a UUV designed for cost-efficient collection of high quality survey data [19], [20]. The system has been developed by the Norwegian Defence Research Establishment (FFI) in conjunction with the Norwegian Underwater Intervention (NUI) and Kongsberg Simrad, with funding from Statoil and the Norwegian Industrial and Regional Development Fund. *Hugin* has been designed for autonomous operations from a wide variety of surface vessels. A series of innovative technologies offer up to 300 km transect range on a single battery charge at 600 m depth, redundant acoustic control *via* bidirectional data transmission up to 2000 m from the host platform, realtime acoustic transmission of compressed multibeam data. *Hugin* provides a cost-effective, flexible platform for a wide range of underwater operations such as: peace time military surveys, multisensor underwater topography, environmental and oceanographic measurements. Technical data are summarized in Table 7.

Length and volume	480 cm, 1.2m^3
Weight	700 kg
Optimum Speed	4 kn
Min. survey distance	50 km with 3 kWh NiCd 300 km with 18 kWh fuel cell
Navigation (on surface)	DGPS or equivalent
Navigation (submerged)	HPR-400, HiPAP or equivalent
Acoustic Communication	Command, Data, Emergency links
Sensors	Vehicle EDO Doppler Speed Log, Seatex Motion Reference Unit, Digiquartz Depth Sensor, Leica Compass
Main Instrumentation	EM3000 Multibeam Echosounder, 1.6 GB storage for EM3000 and sensors data

Table 7 *Technical data of Hugin*

4.3.3 Odyssey

The *Odyssey II* class of AUV was developed at MIT [25] and designed to operate at full ocean depth. The *Odysseys* are small, high performance AUV designed to provide flexible, robust survey systems. *Odysseys* have been proven in a wide range of operational conditions, from coastal operations in high currents, to under ice. Three generations of *Odysseys* have been developed and a fourth generation system with greatly increased range is being designed. The current system is the *Odyssey IIc*. In 1995, five *Odysseys* were built by MIT Sea Grant and used as standard platforms to develop new UUV technology. Design of the next generation UUV is being lead by MIT Sea Grant, but includes important contributions from the Monterey Bay Aquarium Research Institute, the Woods Hole Oceanographic Institution, Florida Atlantic University, Fuel Cell Technologies and Scientific Solutions Incorporated.

Odyssey is a 2.2 m long vehicle, which weighs between 120 and 160 kg depending on the sensor and battery configuration employed. Comprised of a low-drag fairing with a single propeller and cruciform control surfaces, the vehicle is capable of ranges in excess of 60 km at 3 kn, employing its standard AgZn battery set. An equivalent weight lead-acid battery would give a range of 20 km, while lithium primary cells would increase the range to approximately 180 km. A fuel-cell powered UUV is being developed and will be demonstrated in 2000. The system is expected to have a range of 1500 km.

A large number of sensor systems have been integrated into *Odysseys* and employed in experiments including: CTD, sidescan sonar, fluorometer, optical backscatter sensors, 1200 kHz and 300 kHz ADCP, 150 kHz phased array ADCP, eight element acoustic line array, various camera systems including low-light video and acoustic Doppler velocimeter. Figure 3 shows the configuration used in the GOATS'98 experiment [17].

A behaviour-based control architecture is used to provide a flexible and powerful means of specifying mission objectives. A large and reliable library of behaviours has been established and provides a 'tool-kit' from which missions can be constructed. Safety-level behaviors take control of the vehicle should safety conditions be violated. High fidelity dynamic control makes the vehicle a stable yet manoeuverable survey platform. The UUV are routinely operated as fully autonomous systems in which no communication occurs with the vehicle during a mission. Supervisory control of the *Odyssey* is possible through a 200 bps, highly robust acoustic communication.

Odyssey UUV are air shippable. The minimal support requirement is: a battery charger, a PC computer and tools for sealing the pressure vessels. A containerized *Odyssey* arrangement provides a fully self contained facility supporting up to four vehicle and providing for maintenance, tracking and data processing. The vehicles are designed to be operated from a ship or boat of opportunity. They are routinely operated from oceanographic vessels without small boats, an extremely important capability for safe operations. Recovery in conditions up to sea state 5 was demonstrated in the Labrador Sea from the R/V *Knorr*. Operation from launches or even small fishing boats is feasible.

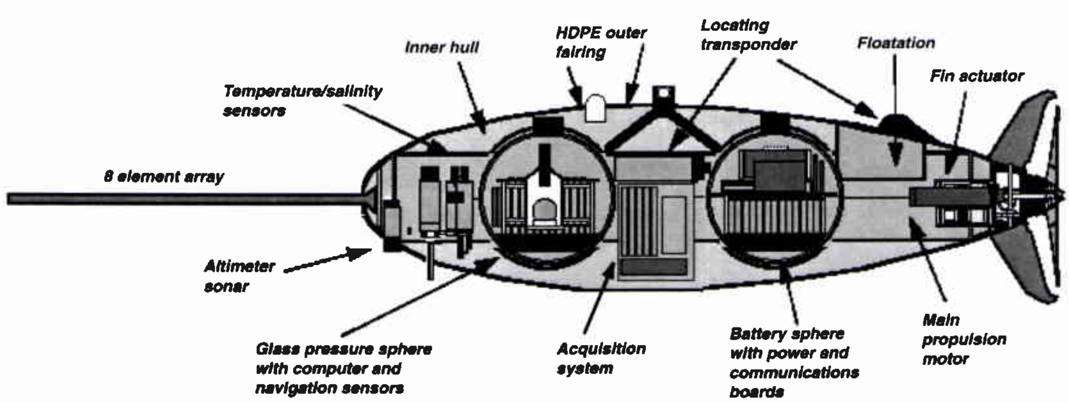


Figure 3 *Odyssey configuration used in GOATS'98 experiment*

4.3.4 Ocean Explorer

Small, low cost, long range vehicles have been developed at FAU as sensor platforms for educational, scientific and military applications [26]. The *Ocean Explorer* (OEX) is not just a single AUV but a new family of AUV's of modular construction, with hull, sensors and software easily convertible for different payloads. The modular payload interface was designed to allow outside researcher to develop in parallel sensor systems that could be easily attached to the AUV, thereby eliminating the need for the sensor developer also to be an expert in AUV design, control and operation. The OEX, designed for daily operations in shallow coastal waters, is small enough to be launched and retrieved from a small boat and yet sufficiently large to hold most sensor systems. In order to maximize usability it is possible to change payloads while at sea.

The OEX's hull shape is a modified hydrodynamically efficient Gertler body shape with a maximum outside diameter of 21" and a length of 7ft to 10ft. The hull is a flooded fibreglass fairing with individual pressure vessels to house electronics. Aft-mounted rudder and stern planes provide directional and depth control. The tail section is about 4 ft long and houses the thruster, propeller, rudder, sternplane, servos, batteries, DVL, depth sensor and main computer. The nose cone is 3 ft long and is left open for payload except for an emergency drop-weight system. The OEX can accommodate parallel midbody insets of 21" diameter from 1 to 3 ft long. Thus the minimum length of the vehicle is 7 ft (tail plus nose cone) and the maximum length is 10 ft (tail plus longest midbody section plus nose cone). The maximum length of the payload is 6 ft. Various sizes of control surfaces have been designed to be swapped in to accommodate changes in control and stability associated with the different hull sizes. A simple bayonet type mounting ring connects the tail and payload nose cone sections. A diagram of the vehicle is shown in Fig. 4.

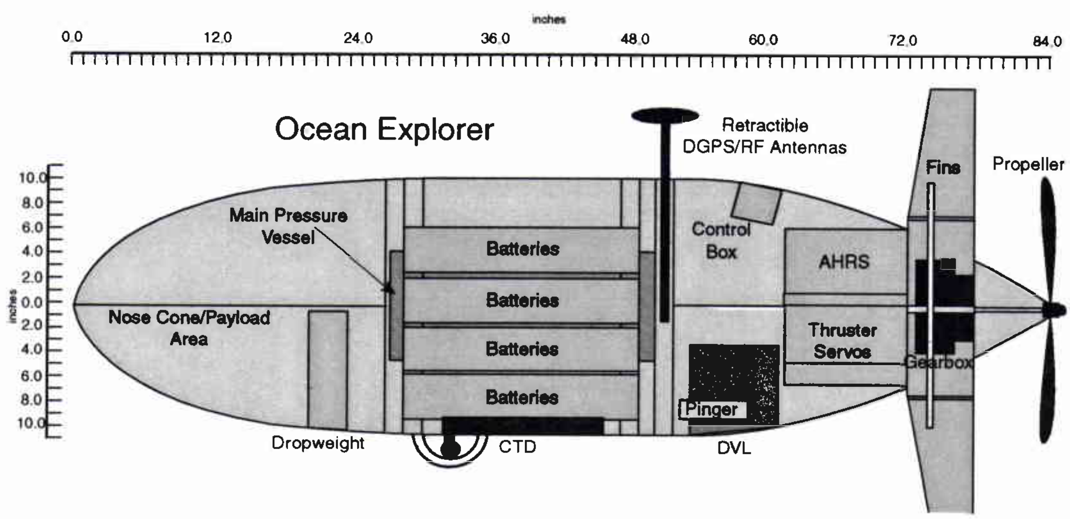


Figure 4 *Diagram of FAU Ocean Explorer*

The propulsion system consists of a brushless DC motor with a 5-1 reduction gear driving a three bladed propeller spinning at 300-500 rev/min. The hotel load for the OEX is around 50 W. The nominal propulsion load for 3 knot operation is around 70 W. A 12 h mission at 3 kn requires 1440 Wh of energy and covers 36 n.mi. A compromise between storage density, cost, modularity and reliability resulted in the selection of Ni-Cad D cells for the power system, which comprises eight modular battery packs, each with 42 D cells and a dedicated microprocessor based monitor and control system. Each pack supplies 4.75 Ah at a nominal 50 V.

In order to integrate seamlessly the multiple payloads available, the OEX uses an intelligent distributed control system (IDCS) based on the Echelon LONWorks [27] control network standard and Motorola 3150 Neuron chip. As shown in Fig. 5, all sensors and actuators on the vehicle are connected on a single serial network by means of a standard connector, with power and network wires, that permits 'plug-and-play' reconfigurations.

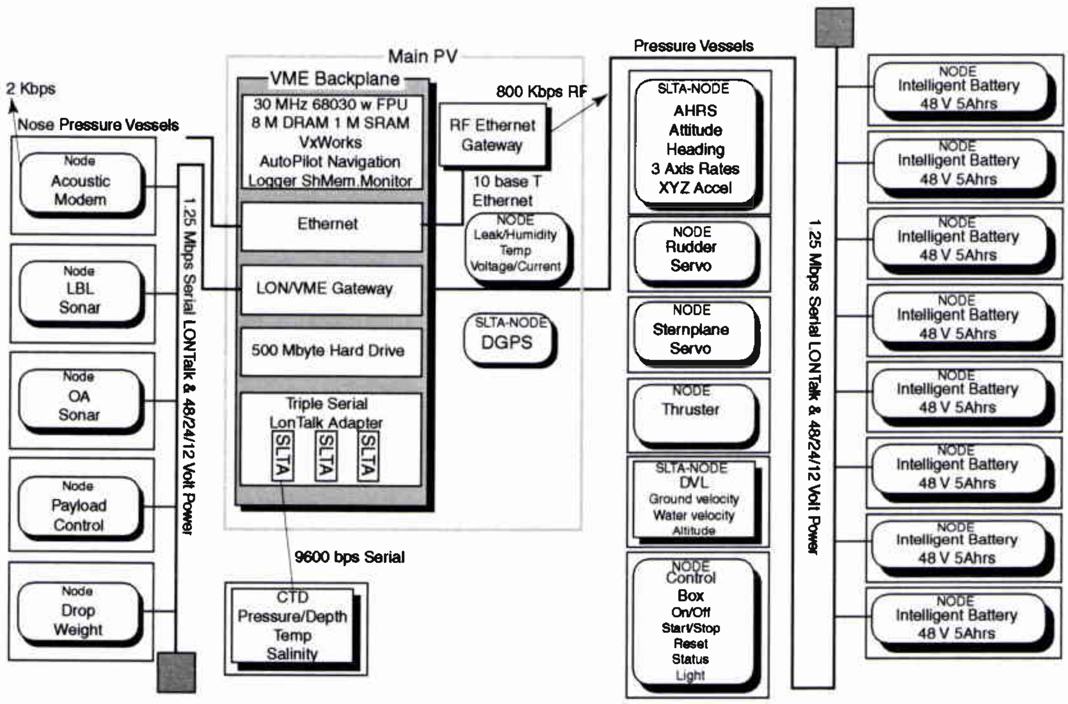


Figure 5 *Ocean Explorer distributed control network*

The architecture allows the addition, removal, modification and upgrading of components and payloads without rewriting the control software or rewiring the vehicle. As all the onboard sensor data are transmitted over the network, this information is available for use by the payload without special programming of the main computer system. For example, a sonar sensor could retrieve pitch and roll information from the network without having a direct connection to the vehicle's main computer. The information currently available to any node on the network includes three-axis attitude, attitude rates and heading, three-axis acceleration, CTD, DVL ground and water column velocity, altitude, battery voltage, status of energy system, stern and rudder positions. Furthermore, portions of the shared memory database on the main computer can be mirrored on the LON network so that the results of position estimation are available to payloads.

As a payload example, a 4 ft long section designed to host a forward looking sonar [28] is shown in Fig. 6. Fitted in the payload are the sonar projector and receiver hydrophone, a 20-inch long pressure vessel and five 200 Wh battery cans. With this configuration a two hour mission is possible using only the payload battery power. The pressure vessel contains a PCI passive backplane, a Pentium SBC, four A/D cards, a SHARC processor, two 9-gigabyte SCSI drives and the necessary power conditioning and regulation boards.

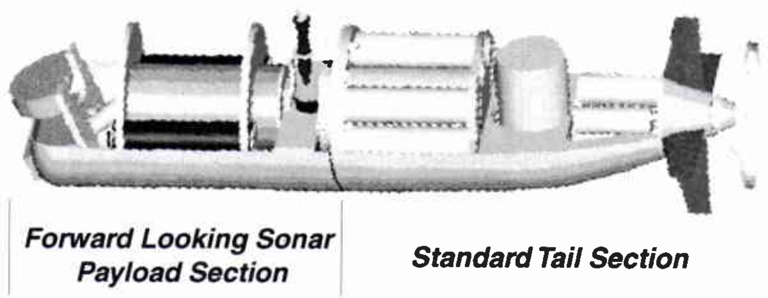


Figure 6 *A forward looking sonar payload for the FAU Ocean Explorer*

4.3.5 Remus

A new generation of Autonomous Underwater Vehicles is being developed at WHOI in support to a number of scientific and military objectives [29]. Despite their small size and low cost, these new vehicles are versatile, reliable and require only a two person support staff. These features make the vehicles affordable and available for missions such as coastal ocean surveys and pollution identification and source tracking. The Remote Environmental Measuring UnitS *REMUS* vehicle is 19 cm in diameter and 134 cm long and weighs 31 kg. It has an operating and control system based on the PC-104 form factor of the IBM-PC which can be connected to a laptop computer for system configuration. With 400 watt-hours of conventional lead acid batteries the vehicle has a useful range of 25 n.mi at 3 kn and a top speed of 5 kn. *REMUS* is capable of navigating itself using a variety of techniques including long and ultra-short baseline acoustic navigation, bottom-lock Doppler navigation and GPS reception. The mechanical design provides a means of docking with seafloor observatories so that the vehicles' batteries may be recharged, their data sets downloaded and reprogrammed for new missions. Because *REMUS* is small, it can easily be transported in a compact car, is air shippable as baggage and may be launched and recovered from a small vessel. Special handling equipment is not required. *REMUS* is based on low cost off-the- shelf technology. The system shown in Fig. 7, consists of the vehicle, a laptop computer running the host program and transponders for ultra-short or long baseline navigation.

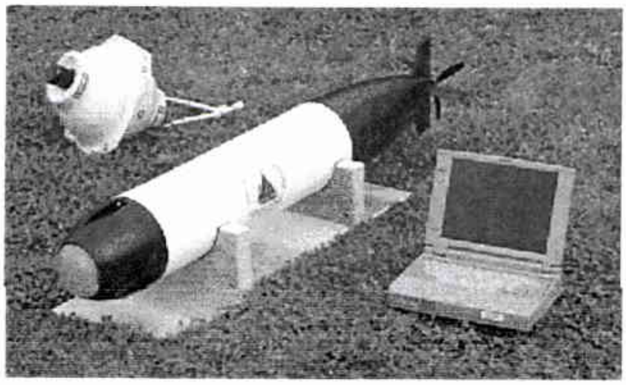


Figure 7 *REMUS Vehicle, Laptop Computer and Navigation Transponder*

At the end of 1997 there were eleven *REMUS* vehicles delivered, being tested or being fabricated for scientific and military coastal oceanography surveys.

4.3.6 FAU mini AUV

In developing UUV, two main paths have been followed: watertight containers of various shapes surrounded by a streamlined spoiler, or a single pressure vessel containing vehicle components and payload. The first approach shows a better flexibility in terms of payload shape and weight, thus conferring to the vehicle a larger field of application, when compared to the fixed overall dimensions of the second solution. FAU designed a hybrid version of the above solutions: the original idea consists in creating a mould for a module, made in composite (GRP), which can be joined together in a very simple way to create the UUV body with the required dimensions. (Fig. 8). The shape of the module is such that many application payloads can be hosted in the UUV without expensive and complicated changes to the body outfitting. Even the cabling is simplified because the modules are fitted with their own underwater connectors to a single cable wiring, which is also running outside the modules. The basic vehicle is composed by the hydrodynamically shaped nose, the tail section which carries the propulsion set with thruster and rudders and the control computer which resides in one standard module. Between the above basic components many standard modules can be assembled (presently up to seven). Multiple modules can form a single watertight container to satisfy payload requirements, by using a junction flange instead of the standard watertight bulkhead. In this way the standardization is preserved. Due to the modular design, it is easy to make this vehicle dynamically stable for any payload. This feature, would be much more difficult to achieve in a body with non axisymmetrical entrained water masses within a flooded spoiler, or with non streamlined payloads attached to the pressure vessel body of the UUV. FAU concept allows buoyancy and weight compensations for individual modules through the spaces available in the redundant cabling wireways. Finally the moulding concept allows low cost outfitting and maintenance and it is likely to set a standard for the payload dimensions and weight.

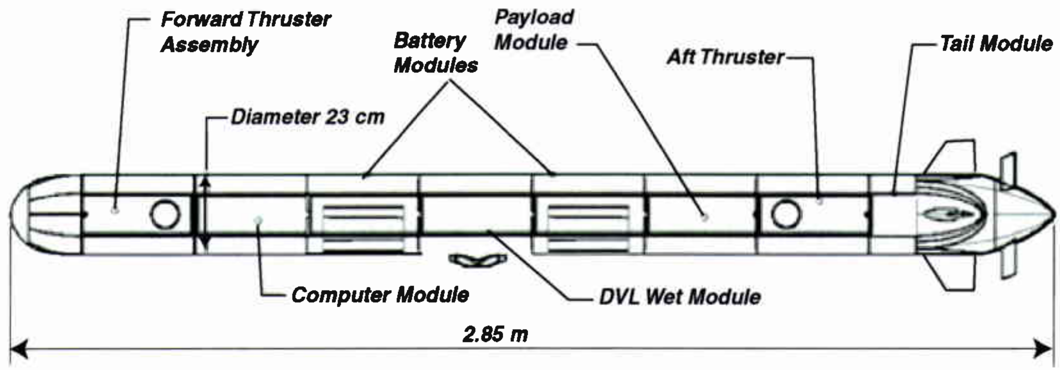


Figure 8 *FAU mini AUV*

4.3.7 The Modular Remote Mine Reconnaissance System (MRMRS)

The Modular Remote Mine Reconnaissance System (MRMRS), is an organic VSW mine reconnaissance mission package to perform clandestine reconnaissance in VSW [30]. MRMRS is a small, stand-off mine reconnaissance mission package for 'Q-Route' surveys and clandestine VSW mine reconnaissance comprised of four Mine Reconnaissance Underwater Vehicles (MRUV), a laptop control console and data links. A single organic helicopter, surface craft or submersible could deploy, control and recover up to four MRUV several miles seaward of the reconnaissance area. The semi autonomous, recoverable MRUV is derived from the Mk 39 EMATT (Expendable Modular ASW Training Target). Like EMATT, it can be air delivered from 'A size' sonobuoy launch tubes or manually deployed and recovered with surface craft or submersibles. The MRUV shown in Fig. 9 has a range of 12 n.mi at 4 kn and is capable of searching a 2,000 yard long × 500 yard wide amphibious assault lane in 2.5 to 3 hours with 100% overlap in sonar coverage or of surveying a 6 n.mi long × 150 yard wide 'Q-route' in 3 h. This 50 in. long × 5 in. diameter/30 lb. UUV is equipped with robotic course, depth and speed control, GPS, long baseline acoustic and sonar Doppler navigation, a side-scan sonar, automatic target detection/classification and either an underwater acoustic or radio frequency (RF) data link to up-link reconnaissance information and receive mission orders from its control platform.

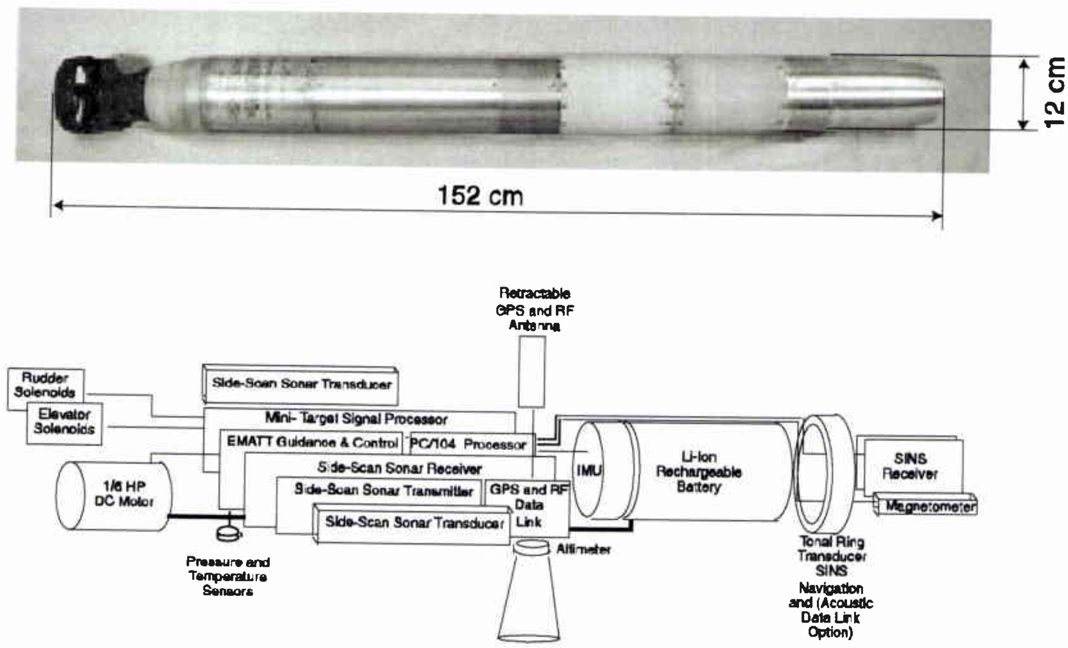


Figure 9 *The Mine Reconnaissance Underwater Vehicle*

5 Technology review

This chapter examines the technology relevant to the development of unmanned underwater vehicles. As many ROV systems are already commercially available, the focus of this section is on AUV and on the recent developments that will allow, in the near future, use of autonomous systems in mine countermeasures.

The development of Autonomous Underwater Vehicle (AUV) systems began many years ago. Most of the original vehicles were simple due to technological limitations, but their potential to serve both military and scientific purposes was apparent. A number of recent efforts have been undertaken to determine, in a comprehensive way, the appropriate role for this technology in different application areas. The academic groups addressing AUV technology include FAU, MIT, WHOI, Penn State University and NPS in the US, SOC and FFI in Europe. In this work, a few key issues have emerged as being paramount, energy systems, high-level control and navigation. Without sufficient energy, nothing can be accomplished and with minimal or possible suspension of communications, the demand for on board decision making becomes critically important. Good navigation is also essential for safe operation and recovery of an autonomous vehicle and necessary to know precisely the geographical location where data are collected.

As shown by the increasing attendance at the annual IEEE AUV Symposia and the biannual International Symposia on Unmanned Untethered Submersible Technology (ISUUST), there is a growing international interest in AUV technology. It is clear from the papers presented that the maturity of AUV technology is mostly in the hardware domain. It is now relatively easy to design a hull structure to some set of operational parameters, construct the hull, populate it with sensors, actuators, computers and batteries and build a self-controlling vehicle. Less mature than hardware, however is the state of AUV software development. Architectures for vehicle software abound in the literature, but to a great extent they have not been tested in practice. Much work remains to be done to properly control the AUV's response to changing conditions in its internal state and in its environment. A review of AUV technology [31] is summarized below.

5.1 Control

The purpose of an AUV control software is the same as that of any other autonomous vehicle: to allow the vehicle to sense, move about in and interact with its world, to survive and to carry out useful missions for its users. The controller can be thought of as a resource manager for the AUV, managing its sensor and actuator use, its power consumption, its location and its time to carry out missions for its users. Survival of the vehicle is also responsibility of the vehicle controller. This includes ensuring a constant internal temperature or power consumption rate, recovery from faults and also taking actions to maintain the current status with respect to the world. For example, the AUV may need to maintain station near a mine; failure to do so could result not only in mission failure, but also loss of the vehicle. The level of intelligence aboard the vehicle can vary, depending on the vehicle and the users' needs. Missions in a static and known environment can be pre-programmed and require minimum intelligence on board, while missions in dynamic or uncertain environment require that the vehicle is capable of autonomous reaction to unforeseen situations.

Until recently AUV control was limited to low-level control (i.e. direct control of sensors and actuators). Lately, however, more attention has been focused on issues related to intelligent control, in particular importing ideas and technologies from artificial intelligence (AI). A major thrust of this effort is to make AUV more capable and less in need of detailed instructions from users. For a discussion of advantages and disadvantages of the various techniques being used, see [31]. This work is however not sufficiently mature to be applied to operational systems and in the immediate future AUV will require some form of supervision by a human operator. This will be achieved by two way communications: from the vehicle to control station in order to inform the operator that some special event has occurred and from the control station to the vehicle in order to modify the mission profile due to the occurrence of external events.

Conventional approaches to AUV low level control rely on a central computer with individual connections to each sensor and actuator. As the number and complexity of sub-systems increases, the effort required to modify, rewire and reprogram becomes prohibitive. Recently distributed control systems have emerged that divide the vehicle into individual control subsystems (called nodes) composed of sensors, actuators and a microcontroller. The nodes are connected together by serial communication link. This allows for reconfiguration at run time and peer to peer access by any component to any information on the network. This approach allows modularity and has the advantage of encapsulating the hardware specific details in each node of the network. By distributing the functionality of the system out from the main computer into the nodes, the reliability and the capability of the overall system increases, while the apparent complexity decreases. Each sensor/actuator subsystem has its own microprocessor with the level of intelligence (i.e. computational power) required to perform default behaviors, self-tests, monitoring and preprocessing of sensor data. This approach facilitates the design of multi-use vehicles, by allowing plug & play reconfiguration without extensive rewiring and reprogramming. Examples of a distributed architectures are the FAU vehicles [32], the *Autosub* [33] and the *Phoenix* [34].

In conclusion, present technology is well advanced in controlling at low level the sensors and actuators of the AUV, but it still lacks the intelligence necessary to make autonomous underwater vehicles truly autonomous. For this reason it is unlikely that in the near future AUV will be capable of performing autonomously all functions related to mine hunting. A human operator is for the moment still required to positively detect, classify and identify mines and to take decisions on unforeseen events. AUV have however sufficient intelligence to conduct preprogrammed missions and are therefore ideal platforms for covert surveys and intelligence gathering. The operator can control the AUV and receive the full data set in real time either with broad band data links (RF as in *Dolphin*) or fibre optic (as in NMRS), but these impose operational limitations to the vehicle. Another alternative is to record on board all mission data and to maintain a low data rate acoustic link between the AUV and the host platform where the operator resides. This allows to maintain a real time knowledge of the vehicle situation (position, speed, sensor and propulsion status) and some limited preprocessed information (coordinates and characteristics of detected objects). The data link allows also the operator to send commands to the vehicle. This is the approach used by *Hugin* that has a two way acoustic link with the mother ship: the low data rate and highly redundant down link is used to control the AUV from the surface, while the uplink has sufficient band to send bathymetry data decimated by a factor of five (i.e. one full image every five transmissions). The issues related to communication and navigation are addressed in the following paragraphs.

5.2 Communications

An autonomous vehicle, by definition, performs tasks under its own control. Its performance is limited, however, by the amount of information in its computer memory and the ability to reason about that information. The ability to communicate allows information to be transferred to and from the system. This in turn allows human intelligence to aid the AUV in performing its tasks. It also allows periodic retrieval of data and information from the system as it accomplishes its defined tasks. The communication link bandwidth required is a function of the amount of data, in the form of messages or data packets, that must be transferred and the amount of time allowed for the transfer. The types of sensors used on the vehicle directly affect the amount of data generated. Video, a primary means of sensing, can produce millions of bits of data every second. Real time video requires a bandwidth of 2-5 MHz. MPEG data compression reduces the requirements to 1 Mbps. Sonar sensors require communications bandwidths up to 100 Mbps. These bandwidths assume that data is being transferred directly from sensor to surface, however if the primary interpreter of data is the AUV itself, data rates can be reduced. Other lower resolution sensor information may be communicated, but in most cases is of sufficiently low bandwidth as to have little impact relative to the requirements of sonar and video information. Table 8 summarizes the typical data quantities and data rates for various sensors and message types.

Data Type	Quantity/Data Rate	Processing
Vehicle position and status	200 bit	Low
Command/Instruction	200 bit	Low
Sonar image	>1Mbps	high
Compressed sonar image	>250 Kbps	Very high
Magnetic sensor	50 bps	high
Target description	500 bit	high

Table 8 *Typical data rates for different sensors and message types*

The requirement for high data rates can be met by fibre optic and RF communication. The fibre optic link is operationally undesirable due to the limited range, its constraints on UUV and host platform manoeuverability and its high cost. RF communication requires that the AUV comes periodically to the surface, or connects to a docking station with RF link to the host platform (directly or through a satellite). Acoustic communication can provide a potential wireless option, but lacks the bandwidth necessary to transfer real time images. Laser technology allows high data rate transmissions at short range. An experiment undertaken by DARPA recently verified the possibility of transmitting 40 Mbps over ranges of 300 ft in relatively clear water. Follow-on experiments increased the data rate to 100 Mbps over a range of 250 ft [31].

New concepts [6], [35], [36] are being considered that would take advantage of network technology to allow communication from an AUV to moored receiving nodes, similar to cellular phone technology only implemented in the underwater environment. This technology shows great promise for large area tasks where resources allow the establishment of fixed nodes spaced a few km apart. An evolving technology that promises great potential is seen in the establishment of low earth orbiting satellites. With world-wide access to cellular telephone technology it is possible to consider an AUV system surfacing for short periods of time (or temporarily connecting to docking stations) and "calling home" to off load data and obtain new instructions. This scenario makes long range transit across the oceans a possibility.

As any electrical or optical cable represent a major obstacle to remote UUV operations, the acoustic communication is widely seen as a vital technology for future UUV systems. The physics of the underwater environment seriously limits the maximum range of transmission as well as the upper limits of data rate. The undersea acoustic channel represents a harsh communication environment due to time-varying extended multipath, the frequency dependent attenuation and the complex boundary interactions. Communication to a mobile platform imposes additional technical challenges. The UUV limited receiver sensor aperture reduces the ability to reject interference from undesired sources or propagation paths; the vehicle self noise limits both data rate and range by reducing the input sensor dynamic range; the relative Doppler introduced by the UUV motion degrades the capability to perform coherent demodulation. Nevertheless the covertness of acoustic communication is operationally attractive for controlling an underwater vehicle and for exchanging a limited amount of information.

Traditionally non-coherent modulation and frequency diversity were employed to mitigate channel effects, but these techniques suffer from poor bandwidth and power efficiency resulting in limited data rates and range. Recent advancements, in the area of bandwidth efficient modulation schemes such as M-ary PSK, have offered significant improvement in performance [66]. In order to maximize data the PSK signal must occupy all of the available channel bandwidth and therefore no spread spectrum processing is possible to combat the effects of multipath and noise. Furthermore since PSK requires phase coherent detection, Doppler effects must be removed for successful demodulation. This has led to the development of complex receiver structures employing adaptive equalization and/or adaptive arrays, combined with explicit Doppler compensations. Adaptive equalization involves attempting to achieve an inverse filter to the communication channel and continually adapting the coefficients (taps) of the filter to variations in the channel. Adaptive array processing falls broadly into two categories; beamforming and spatial diversity. The former involves manipulating the angular response of a narrowly spaced array (of the order wavelength) to null out interference signals which are angularly separated from the desired signal. The latter involves the coherent combination of signals from widely separated array elements so as to achieve a diversity gain (i.e. interference signals are uncorrelated between elements). Unlike equalization, these techniques can be equally effective against noise sources (such as shipping) as they can against multipath. These techniques can also be combined with the channel equalization algorithms to form a jointly optimized structure, which has proven to be the near optimal receiver for acoustic data communication systems.

Low data rate acoustic telemetry systems have become commercially available. These systems, based on non coherent detection, allow relatively low data rates (600-2400 bps) to be transmitted over ranges of a very few kilometres [37]. New coherent modulation techniques such as DPSK, have recently increased the data rates possible to 20000 or more bits per second over ranges of a few kilometres. Figure 10 shows the achieved data rate *versus* range for coherent and non coherent technologies [38].

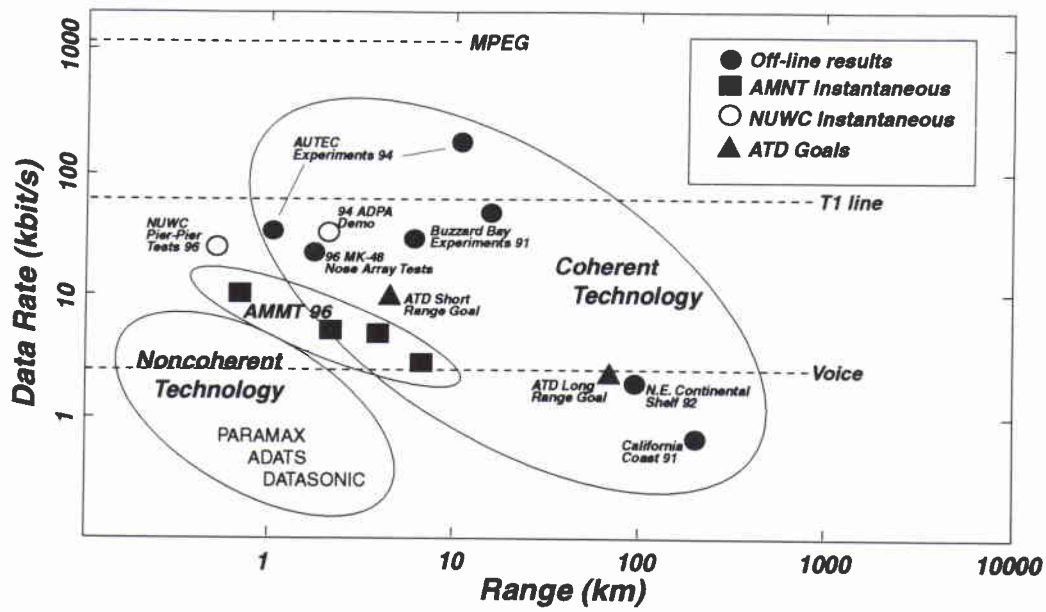


Figure 10 *Comparison of coherent and incoherent communication technology*

Figure 11 shows the comparison of theoretical limits of channel capacity to experimental data. The dotted curves represents the theoretical upper limit on reliable communication rates established for various frequencies and environments based on transmission loss and information theory, the dots represent performance demonstrated during recent experiments, the stars are the short, medium and long term goals of the ONR UUV communication technology program [38].

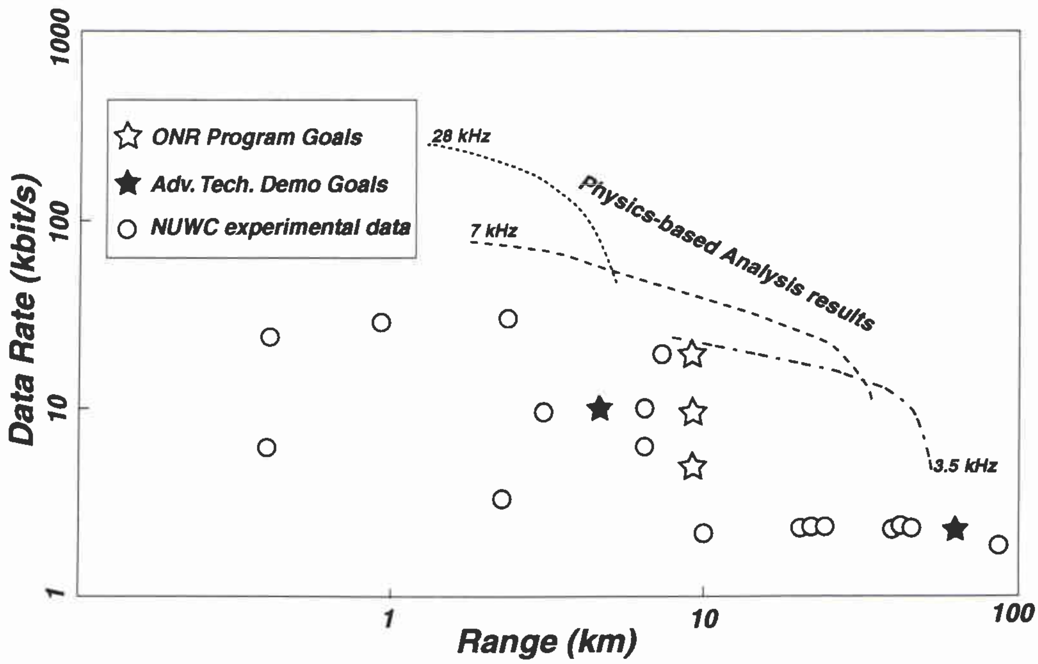


Figure 11 *Comparison of theoretical limits and experimental data*

In summary, for UUV operating in shallow water within a few km radius of mother vessel, reliable communication at data rates up to 20kbits/s seems a realistic prospect. This would allow slow scan video images to be retrieved [39], [13]. Simultaneous low data rate control messages to the UUV are also possible [14].

The following limitations must also be addressed in future work:

- The limited bandwidth available leads to serious problems if multiple systems are to operate in the same area.
- Particularly in fast moving vehicles, the noise and wake generated by propulsion systems is an unquantified problem as yet.
- Many UUV have onboard sonar systems that are likely to interfere with communications and *vice versa*.
- The high source levels involved in acoustic telemetry are likely to become an increasing environmental concern as usage becomes more widespread.

5.3 Navigation

Navigation is an important requirement for any type of mobile robot, but this is especially true for underwater vehicles. Good navigation information is essential for safe operation and recovery of an AUV and necessary to know precisely the geographical location where data are collected. Some of the important concerns for AUV navigation, such as the effects of acoustic propagation, are unique to the ocean environment; others, such as managing uncertainty, are common to mobile robot research. There are currently several technologies either in use or proposed for AUV navigation: dead reckoning and inertial navigation systems (INS), acoustic beacons and geophysical navigation [40].

The longest established navigation techniques are dead reckoning and the self-contained inertial navigation system (INS). Dead reckoning systems combine the velocity information provided by a Doppler Velocity Sonars (DVS) or Correlation Sonar (CS) with the heading provided by an heading sensor. This technique requires a high precision heading sensor: to match a 0.1% Doppler, an accuracy of about 0.01 deg/h at 60° latitude is required [41]. A medium cost dead reckoning system can achieve 1% to 3% of the distance travelled.

The INS is based on gyroscope and orthogonal triad of accelerometers. The accelerometers output is integrated twice in time to estimate the vehicle position relative to a reference starting point. The accelerometer assembly is referenced to the Earth coordinate system by means of a gyroscope that maintains a precise attitude reference. The problem of this technique is that position error increases without bound with the distance travelled. The accuracy standard of the industry is on the order of one mile per hour of navigation for cheap systems, up to one tenth of a mile an hour for carefully manufactured and calibrated systems. However the requirements of the military and commercial survey community are much more stringent, in the order of tens of metres of position error over several hours of operation. The methodology for achieving such performance, using a medium accuracy one mile per hour inertial system, is to use a Kalman filter coupled with good observation of the velocity error [42]. In land robot this is achieved by periodically stopping the vehicle, the so called zero velocity update (ZUPTS). In AUV DVS or CS sensors can be used to measure the velocity relative to the sea floor. The integration of this information in the navigation Kalman filter can greatly improve performance. Although extreme navigation performances of 0.01% of distance travelled using an integrated INS/DVS have been reported [43], current aided INS systems that can be installed in AUV are likely to achieve only 0.05% of distance travelled.

Inertial systems have made great progress over the past ten years. Laser gyro systems currently under development offer the potential for on board navigation capability of reasonable accuracy for many missions [44]. They are also small enough to fit into most AUV. When integrated with velocity updates (such as Doppler or correlation velocity sonar) their accuracy is improved and if periodic position updates are used (such as from GPS) they allow AUV to travel over large ocean areas. The capabilities of fibre optic gyros (FOG) continue to increase. Several companies now manufacture units for application in automobiles (navigation) and airplanes, called attitude-heading reference systems (AHRS). These offer the potential for inexpensive, small, low power, lightweight, extremely rugged and virtually maintenance-free navigation systems. The near term INS/GPS error budget and cost is shown in Table 9, derived from [44].

Accelerometer Technology	Silicon Micromechanical	Quartz Resonant or Silicon Micromechanical	Quartz Resonant or Silicon Micromechanical	Quartz Resonant or Silicon Micromechanical
Bias Stability (μg) 1σ	1000	200	100	50
Gyro Technology	Silicon Micromechanical	Silicon Micromechanical or Fibre Optic Gyro	Fibre Optic Gyro	Fibre Optic Gyro
Bias Stability (deg/h) 1σ	10	1	.1	.01
INS production cost	$500	$1000	$10000	$20000

Table 9 *Near term INS/GPS systems*

Acoustic navigation systems are the most widely used [45], [46]. The most widely used types are: long base line (LBL) and ultrashort baseline (USBL). In LBL navigation systems an array of transponders is deployed and surveyed into position. The vehicle transmits an acoustic signal which triggers the transponder response. Position is determined by measuring the travel time between the vehicle and each beacon. The accuracy of the system depends on the frequency used and the distance between beacons. Table 10 summarizes the performance of typical systems

Frequency range	Maximum range	Typical relative accuracy
8-16 kHz	>10 km	2-5 m
18-36 kHz	2-3 km	.25 -1 m
30-60 kHz	1500 m	15 - 25 cm
200-300 kHz	<100 m	<1 cm

Table 10 *Relative accuracy of typical LBL systems*

A variant of LBL is hyperbolic navigation, in which the vehicle does not actively ping but listens to an array of beacons the geometry of which is known. Each beacon pings in a specific sequence relative to the others at its specified frequency. The vehicle computes its position from the received signals. This system has the advantage of saving the power necessary for active pinging and is especially useful for multiple AUV operations.

In USBL navigation, the vehicle interrogates an acoustic transponder and measures its bearing and range by means of a multi-element receiver array. Knowing distance and direction to the beacon allows for local navigation, knowing also its latitude/longitude coordinates allows for geodetic navigation. This type of system is especially effective for homing and docking operations which are important for AOSN deployments [47].

Errors in both LBL and USBL come from primarily two sources: errors in the assumed array geometry and errors in assumed sound speed profile. Positioning errors come from inadequate surveys of the relative and/or geodetic positions of the transponder arrays. However sophisticated software packages and self calibrating beacons are available to simplify the task of navigating the beacons array. An inaccurate sound speed profile will appear as a distance bias in the range calculations. Multipath is also responsible for timing errors and hence erroneous position fixes. In general acoustic navigation is very reliable, with good accuracy, but is range limited by acoustic propagation. For local area missions of hundreds of metres to a few kilometres, where positioning accuracy is important, acoustic systems are well suited to the task. The only drawback is that transponders must be placed in the area and for the long baseline case, must be calibrated.

For some AUV applications (for example long range covert reconnaissance) the use of acoustic beacons is undesirable or impractical. If an accurate *a priori* map of the environment is available, measurements of geophysical parameters such as bathymetry, magnetic field, or gravitation anomaly can be utilized to estimate the vehicle position [40]. AUV navigation based on bathymetric data has been successfully demonstrated by Bergem [41]. In this system depths are measured at different angles using a multibeam sonar to produce an accurate profile of the sea floor. The absolute position is determined by matching this profile against an a priori known detailed bathymetric map of the area. Bergem reports bounded errors of approximately 40 m without using speed sensor information and states that the additional information provided by a Doppler log sensor with 0.05 m/s accuracy allowed to achieve positional errors similar to differential GPS (few metres).

In practice however, a sufficiently precise and up-to-date map of the area of interest may not be available or may be too expensive to produce: this motivates research into the problem of concurrent mapping and localization (CML) [48],[49],[50]. The goal of this approach is for the AUV to build a map of its environment and to use that map to navigate in real time. A basic problem of CML is the identification and recognition of natural features in the environment. Sonar data are difficult to interpret, they usually have insufficient information to determine the shape of an object and are often corrupted by multiple reflections and multiple paths. The fundamental capability required is to combine the information provided by multiple sonar returns obtained from different sensing locations [40]. This is the subject of active research that is motivated by the ability of bats and dolphins to navigate very efficiently in cluttered environments using their sonar. Although very attractive from an operational point of view, CML techniques are still the subject of fundamental research and are not considered viable solutions for the navigation of autonomous vehicles in the near future.

Radio frequency beacons are also used in AUV navigation and GPS/DGPS receivers are being integrated in the vehicles or in surface buoys used for navigating AUV. When the AUV is on the surface or near the surface, it can determine its position by means of a GPS/DGPS receiver mounted on a retractable mast or on a vertical fin. Commercial systems are becoming available that are optimized for acquiring GPS fixes even in presence of severe antenna wash-out. The drawback of this approach is that vehicles operating close to the coast, or to a shipping lane, risk the danger of collision with surface vessels. Furthermore, in deep water applications, it may not be practical to surface due to time and energy constraints. Non traditional systems based on GPS Intelligent Buoys (GIB) are also proposed to navigate and control multiple AUV [13].

To conclude the overview of AUV navigation, it should be noted that the best navigation performances are achieved when flexible architectures are used to combine data from different navigation systems. Smith [51] has developed and successfully demonstrated at sea, a robust algorithm to implement asynchronous data fusion from a suite of navigational sensors, which accommodates any combination of relative and geodetic navigation instruments.

5.4 Sensors

Sensors, that are integral components of the AUV can be subdivided into the categories below.

Obstacle Avoidance Sensors: Most AUV missions require the vehicle to avoid objects in the water column. This may not be very significant in blue water operations but is critical when operating in coastal waters. There are many sonar systems on the market which can be adapted to avoidance, or which can serve the dual purpose of sonar imaging and avoidance.

Reference Sensors: This category of AUV sensors is essential to AUV control. The technology is in common use and includes sensors to measure vehicle depth (pressure and sonar), altitude above the bottom (sonar), heading (compass, AHRS), pitch and roll, thruster rotations/min and control surface angles.

Self-Diagnostic Sensors: AUV's by their very nature must maintain their own system "health" and safety. This requires having and monitoring leak detectors in pressure housings, energy consumption and rates of consumption, internal temperatures and water temperature (for acoustic systems), etc. The real problem is to have software and control strategies that are able to impact the system response to recognized problems. There is significant research interest in the development of software able to recognize and deal with expected and unexpected failures to system and subsystem components.

Mission Sensors: These sensors are unique to particular types of missions. Some common types are for video imaging, laser imaging, sonar systems and magnetometry. In addition, ocean scientists are becoming increasingly interested in AUV and there is much effort now underway to address the problems of integration and long term calibration of scientific sensors on AUV's. In general, the development of hardware to acquire data has surpassed the development of the software required to autonomously understand the information inherent in the acquired data.

Traditionally MCM sensor technology has focused on imaging systems; it is interesting to compare MCM sensor resolution for the operations of detection, classification and identification. Figure 12 shows the resolution at maximum range for typical MCM sensors versus the corresponding search rate [52].

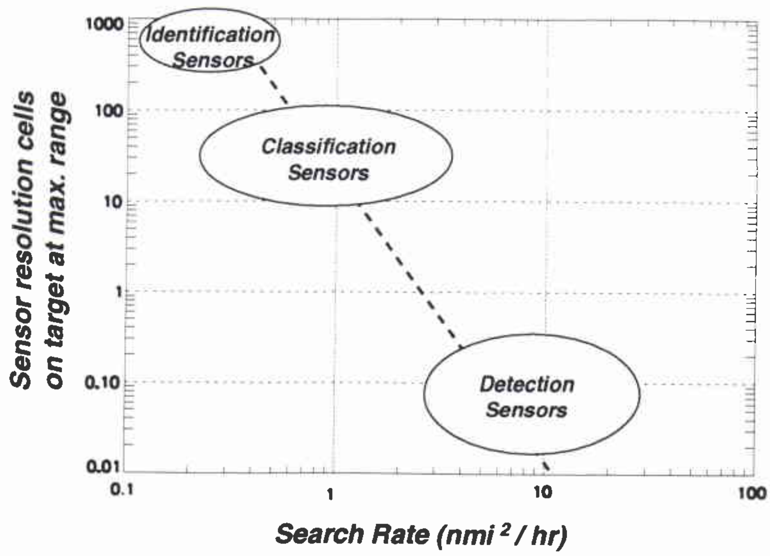


Figure 12 *MCM Sensor Performance*

Acoustic sensors are used for detection and classification, while optical sensors are utilized in the identification phase. As sometimes acoustic and/or optical information is not sufficient to detect and identify mines (e.g. as in the case of buried mines), magnetic sensors are also used in MCM.

5.4.1 Acoustical Sensors

A variety of sonars can be fitted to AUV: forward looking sonars, toroidal sonars, side looking sonars and multibeam echo sounders.

Forward looking sonars fulfill the dual function of obstacle avoidance and forward imaging. They use planar arrays mounted in the nose of the vehicle, operate at high frequency (300 to 500 kHz) and have range resolutions better than 10 cm. Angular resolutions better than 1° are achieved by beams electronically steered in both vertical and horizontal planes. They usually cover a 90° sector in front of the vehicle and allow detections up to a few hundreds of metres. Their dimensions and power requirement are compatible with a medium size AUV. The performance of forward looking sonars is limited by the small aperture available in the front part of the vehicle.

Toroidal and side looking sonars overcome this problem by fitting the transmit and receive arrays on the side of the vehicle. Toroidal sonars such as the TVSS developed by Coastal System Station [53] are suited for hunting volume mines. TVSS uses 120 receive elements distributed in a band around a section of a 21" vehicle, to form 120 pencil beams 3° wide. The transmitter is also in a band around the same 21" section and projects a uniform 360° transverse beam that is 3° wide in the azimuthal plane and has a bandwidth of 12.5 kHz (thus providing 5 cm resolution). The projector and receive shell section are each 60 cm long. Working at 68 kHz, the TVSS has a range of 675 m and an area search rate of 6 n.mi^2/h at 8 kn.

Side looking sonars are well suited to be fitted on each side of the AUV. They consist of a transmitter insonifying a water volume perpendicular to the motion of the vehicle and of a long receiving array that allows a very high azimuthal resolution. The vertical transmit beam is usually wide (50 to 80°), to maximize bottom coverage and downward tilted, to avoid surface reverberation. The azimuth transmit beam is narrow (3 to 5°) to reduce reverberation entering through the sidelobes of the receiving beams. The long baseline of the receive array allows very high angular resolution of targets and shadows.

The performance of side looking sonars deteriorates at angles near vertical incidence due to the strong return of the sea floor and there is a gap in coverage just below the vehicle. This problem can be overcome by using the information of the forward looking sonar, by designing a dedicated gap filler sonar, or by covering the gaps with multiple passes over the same area. A significant advantage of side looking sonars is that it is possible to further increase their angular resolution by using synthetic aperture techniques. This is particularly attractive at lower frequencies (necessary to detect buried or partially buried targets) that would otherwise require impractically long receiving arrays. Examples of high and low frequency SAS are the sonars developed by CSS for the HARR and MR/H programs [53], [54]. Compensation of sensor motion is an issue for the correct formation of the synthetic aperture, but recent developments of autofocusing techniques [55], together with the improvement of INS , make this approach practical and cost effective. Furthermore the inherent excellent estimation of the platform motion that derives from these algorithms can be used to improve the navigation of the vehicle.

The geometry of the transducers and the beam patterns of a multibeam sonar system is shown in Fig. 13. The transducers send narrow band acoustic signals towards the sea bottom and receive echoes for bathymetry computation. The transmitting array is mounted parallel to the vessel's motion direction and thus transmits a fan shaped beam in the cross direction. The receiving array is mounted perpendicular to the transmitting array and forms a number of received beams at different angles. The echo coming from each intersection of the transmitted and the received beam footprint is then detected. The arrival time and the direction of the echo provide information to compute the bottom depth z and the cross track distance y. When the location of the vessel is given and the effects of sound ray bending and the roll, pitch, heading and heaving movements of the vessel are compensated, z and y can be transformed to the sea bottom location in a global coordinate system. The *Hugin* AUV is a good example of a this type of configuration

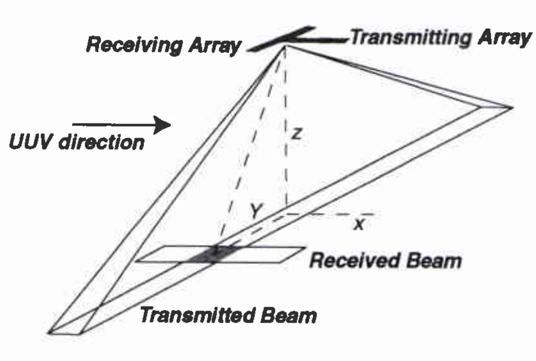


Figure 13 *Multibeam sonar geometry*

The payload of *Hugin* consists of a modified EM3000 multibeam echo sounder and a disk mounted in a separate watertight container. The EM3000 processing unit (PU) receives setup information, commands and navigation sensor data from the vehicle control system (VCS) and logs multibeam and navigation sensor data to the disk. The EM3000 PU also sends compressed multibeam data to the VCS for transmission to the surface host vessel to be used for real-time quality control. The disk is dismounted after each mission for offloading and post-processing using standard multibeam postprocessing utilities. The navigational sensor data logged on the payload system disk is combined with surface navigation data in a Kalman-based postprocessing filter. This improves the position and heading accuracy significantly. As an example [56], for a mission with the UUV 50 m above the seabed in 300 m of water, 141 m off the survey vessel, the Digital Terrain Model (DTM) derived from the EM3000 multibeam sonar had a position uncertainty of 1.4 m.

5.4.2 Optical Sensors

Optical mine hunting sensors range from simple camera systems that rely on natural light for illumination, to sophisticated range gated and laser line scanning sensors. The ranges achieved run from about one optical attenuation length from the simple camera based systems to five or more attenuation lengths for the laser systems. Attenuation lengths can vary from 1 m or less in turbid waters, to 5 m or more in clear waters. The resolution deteriorates with increasing range, but typically 1 cm resolution or better can be obtained, providing therefore an excellent identification capability [53].

Underwater video cameras have been used on manned submersibles and remotely operated vehicles (ROV's) for a long time; their main disadvantage is their short range of operation in turbid waters. Laser sensors are being developed to overcome this limitation.

This laser field is rapidly developing with much research and development underway. Although the distances over which lasers can be used in the water column is not great (tens of metres), they have extremely high resolution. Two approaches are pursued, the laser line scan (LLS) and the laser range gated (LRG). LLS systems reduce the effect of backscatter noise and blur/glow/forward scatter noise by syncronously scanning a narrow laser beam and a narrow field-of-view receiver across the sea bottom. LRG imaging systems perform significantly better than conventional systems because they reduce the impact of reverberation by gating it out in time.

The Coastal System Station of the Naval Surface Warfare Centre has evaluated both technologies [57] and has concluded that the both LRG and LLS system can detect targets at relatively long range in turbid waters, but only LLS have the necessary contrast and resolution required for mine identification. They have consequently focused on the development of a LLS system that provides high resolution (6 mm) at long range (five optical attenuation lengths) in a 21" section 81 cm long, consuming only 285 W of power. Its relatively large range is especially valuable as it reduces the positional accuracy required in the difficult target reacquisition process.

The drawback to integrating these systems on AUV's is that there is no human on board to interpret the images in real time. Alternatively, video can be transmitted to a remote operator for analysis. Bandwidth compression research is receiving increased interest with the availability of high data rate acoustic transmission up to 20 Kbps or greater. Further development in these areas may allow transmission of compressed images from AUV in the future [39], [13].

5.4.3 Magnetic Sensors

Magnetic sensors have proven merit [58] for mobile area surveys and search operations for the localization of sea mines: long-range detection is required for reconnaissance and hunting in preparation for an amphibious assault and short-range detection is required for diver mine detection and avoidance. The performance of a magnetic sensor is measured by its detection range, which depends on the sensitivity of the sensor and the magnetic moment of the target of interest. There are two types of magnetic sensors: those which detect changes in the local magnetic field, called magnetometers and those which measure the spatial derivative of the magnetic field, called gradiometers.

A number of sensors, such as fluxgate magnetometers and superconducting magnetometers, are well suited to measure the individual vector component of the magnetic field in static conditions and are therefore useful in localizing targets for stationary applications. However these sensors are not effective in mobile applications as they are not able to compensate the undesired signals arising from the sensor motion in the Earth's magnetic field. Other magnetometers, called total field magnetometers, measure the projection of the target magnetic field onto the Earth's field and lack valuable target vector information.

Gradiometers measure the gradient of the magnetic field and offer the potential to remove many of the limitations associated with magnetometers because their output is usually produced by twin magnetometers operating in differential mode. In particular this configuration provides common-mode rejection of the temporal variations in the Earth's field and of the field changes induced by the sensor rotation in the Earth's field. Gradiometers may be fabricated using many available magnetometer technologies. Fluxgate and total field magnetometers can perform at levels approaching 1 to 10 pT, while Superconducting Quantum Interference Devices (SQUIDs) can perform at levels on the order of 1 to 10 fT. The performance of superconducting magnetometers allows fabrication of high sensitivity gradiometers with short baselines, providing a compact package with very high coherence between magnetometers. The coherence is necessary to maintain high performance when in motion and the compact package is suited for UUV application.

The signal strength of a magnetic dipole decreases as the third power of the range for magnetic fields and as the fourth power of the range for magnetic field gradients. The approximate ranges of magnetometers and gradiometers are displayed in Fig. 14 as functions of dipole strength and sensor sensitivity [58].

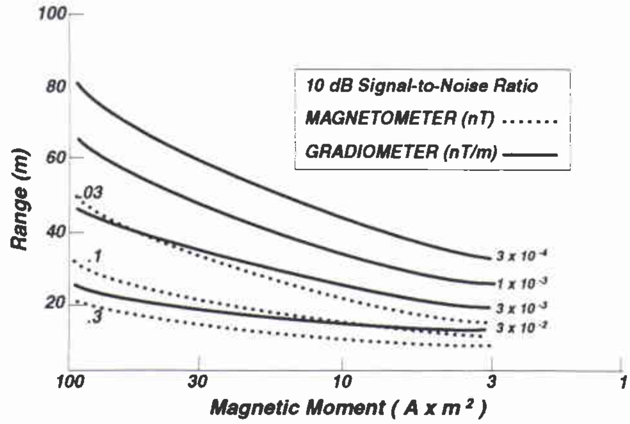


Figure 14 *Approximate detection ranges of gradiometers and magnetometers*

It should be noted that the high rate of signal reduction with the fourth power of distance in the case of a gradiometer represents an apparent shortcoming for a gradiometer configuration. However, the ability to develop gradiometers with sensitivities greater than 10-3 nT/m for mobile operation and the extreme difficulty in utilizing magnetometers with sensitivity greater than 0.1 nT in mobile applications significantly outweighs this shortcoming. Current technology uses niobium (Nb) superconducting components and is close to its performance limits, while new developments in nitrogen cooling allows the development of sensors utilizing high Tc materials, thus providing an opportunity for significant size reduction and ease of maintenance relative to the low Tc technology with helium cooling. For a review of current gradiometer development status, see [58].

It is expected that soon high Tc devices will be available with performance comparable to that which has been demonstrated with low Tc devices (i.e. about 50 times better than the best commercially available fluxgate magnetometers). The localization capability afforded by 5-channel gradiometers (and not previously available by conventional magnetic sensors) is expected to add impetus to the acceptance of magnetics for mobile applications.

5.4.4 Sensor fusion

Active acoustic systems are effective in detecting moored and proud mines in deep and shallow water, however the very shallow water bottom mine and the buried mine are very difficult or impossible to detect with acoustic means. Interfering reverberation from the air/sea and the sea/bottom interfaces, bottom topographical features and mine burial present a difficult acoustic environment for the detection of mines. Moreover, in coastal regions the density of debris clutter may lead to a high false alarm rate using conventional imaging sonar approaches alone. For effective clutter reduction it is very desirable to fuse the information coming from different sensors to reduce false alarm and to improve the detection performance in a wide variety of background conditions. For the detection and classification of mines the combination of magnetic sensors with sonars provides such an alternative.

Often the adverse environmental characteristics and the weak target signatures do not allow reliable detection and classification of mines with only one type of sensor. Multiple observations of targets and associated clutter by sensors detecting different physical phenomena allow lowering individual sensor thresholds to ensure that each sensor detects all targets and clutter of interest. Sensor fusion is then used to reject clutter.

This approach has been used, for example, in the Magnetic and Acoustic Detection of Mines (MADOM) system targeted to the detection of buried mines [59]. A triad of sensors (superconducting magnetic field gradiometer, synthetic aperture sonar and side scan sonar) was used to provide independent and complementary looks at the targets and associated clutter. When a single magnetic sensor was used to survey an area of interest, hundreds of potential targets (mines and clutter) were identified. Similarly, the acoustic sensor alone made hundreds of contacts when surveying the same area. However, when the target information was fused and targets were required to be spatially correlated and showed both acoustic and magnetic mine-like qualities, clutter targets were easily identified, thus reducing the number of mine-like targets of interest by two orders of magnitude. The key to this success was to lower the sensor detection threshold so that very few real targets of interest would be missed. This in turn resulted in the adverse effect of increasing the clutter contacts, it was however essential to maximize the probability of detection. Clutter was rejected by requiring that spatially correlated contacts exhibit mine-like qualities in the sensor combination. Implicit to the success of this strategy is the necessity to accurately localize and separate individual targets with each sensor. Errors in co-registration can actually complicate the problem by introducing false contacts.

Several investigation have been conducted recently using automated neural network to assess the merit of magnetic and acoustic data fusion [60]. Using the data collected at sea with the Superconducting Gradiometer Magnetometer Sensor and the MADOM low frequency synthetic aperture sonar developed at Coastal System Station, a set of 215 magnetic detections and sonar images containing an assortment of drill targets and clutter objects has been assembled. Figure 15 shows the probability of detection and classification for acoustic and magnetic sensors alone and for neural network fusion data from both sensors given as a function of the number of false alarm per image. It is clearly evident the advantage of integrating acoustic and magnetic information [60].

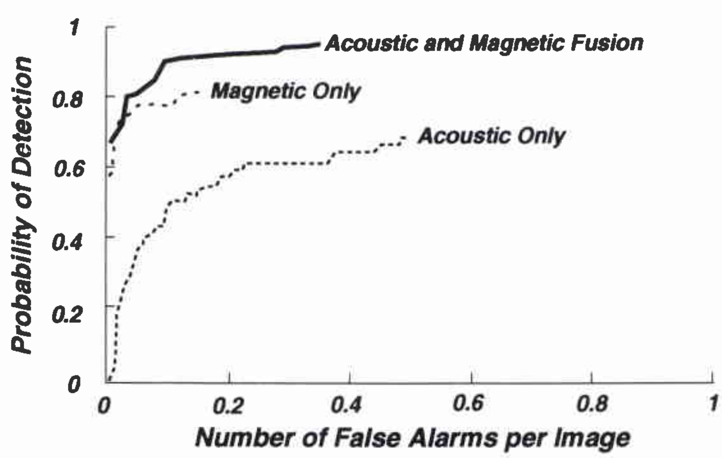


Figure 15 *Probability of classification vs false alarm per image for acoustic and magnetic sensors*

Commercial systems integrating sidescan sonars and gradiometers (such as the Klein 2000 and the Geometrics Cesium Magnetic Gradiometer G880G) are starting to appear on the market[13]. The integration maintains the basic system integrity of each subsystem, allowing each to be used separately or together. In integrated mode, power and data multiplexing are supplied from the System 2000 to the G-880G, which is towed eight metres behind the side scan sonar. In the host platform the magnetometer data is separated from the sonar data by the System 2000 Display/Processor unit and transmitted to the Geometrics Data Display and Processing Unit. The magnetic gradients and sonar data are concurrently logged with GPS position data and are displayed on a PC based data acquisition and processing station. The combined data affords improved target acquisition, accurate spatial plotting and characterization of target size and depth.

5.5 Energy sources

The amount of energy that an AUV carries on board limits its operational utility. The system must be able to provide all of its own power and manage that power in such a manner as to ensure its ability to return to the support ship or platform. AUV's will not reach their real potential until better energy systems are available. There is no clear answer at this time as to which energy system is best.

Lead-acid secondary batteries have been used for various vehicle applications for decades, despite significant disadvantages with respect to energy density. Advantages of cost, availability and known performance will probably support their continued use in underwater vehicles with limited range and endurance requirements where cost is a major consideration. Silver zinc batteries have characteristics which make them a good choice. Their cost, however, has limited their acceptance. Lithium batteries have a very high energy density and are relatively available as commercial products. The potential safety hazards associated with these systems must be traded off with the increased energy density. The ability to recharge nickel cadmium batteries and their increased energy density over lead acid batteries make them appealing in some applications. Cost and other factors, however, must temper the final choice. A recent application of sea water batteries uses magnesium anodes and the dissolved oxygen in sea water to develop energy for an AUV [61]. This system has the advantage of very high energy density and relatively low cost but has a limited output power capability. Movement of sea water over cylindrical arrays of magnesium anodes provides the oxygen necessary for operation.

A number of new energy systems offer increased potential for many AUV systems. Many are still under development but will soon offer promising alternatives with significant increases in performance. Aluminum oxygen systems are being developed and tested by several companies. Zinc oxygen semi-cells offer the potential for significant power densities at relatively low cost. More importantly, the system generates little hydrogen, thereby eliminating some of the safety hazards of many high energy systems. Fuel cells promise high energy densities appropriate for AUV systems, but cost and reliability factors as well as ease of use and maintenance must still be addressed.

[13] http://www.kleinsonar.com/mag/mag.html

Required propulsive power for UUV of 2 to 3 feet in diameter ranges from a fraction of a kilowatt to as much as 20 kW as speed increases from 1 to 20 kn. The power relationship is exponential and is small relative to typical hotel loads at low speed and high relative to them at high speed. This gives rise to an optimum operational speed for maximum range because low speeds cause too much energy to be expended on the hotel load. The critical impact of hotel load is illustrated in Fig. 16 which shows what happens when a 26.5" diameter vehicle is fitted with a large enough energy section to go 300 n.mi with a 500 watt hotel load and is then operated with a 1500 watt hotel load. The maximum range falls to less than half the original range, while the optimum vehicle speed increases from 4 kn to about 5.5 kn. This example is illustrative of the commonly encountered significant range reductions that are associated with higher than anticipated hotel power [62].

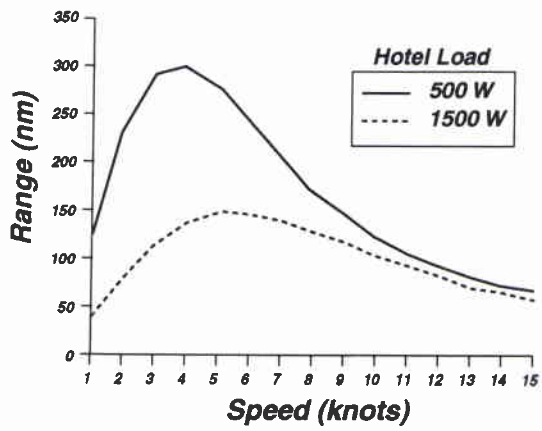
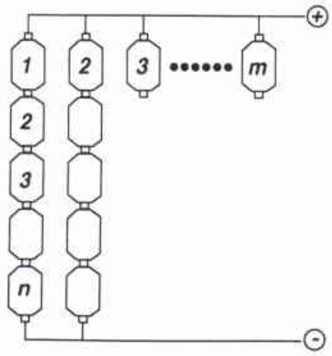


Figure 16 *Maximum range for a 26.5" diameter UUV with different hotel loads*

Efficiency, cost and the ability to produce vehicle turning moments at low speeds are the principal design drivers for motor/propulsor assemblies. Batteries, fuel cells and thermal hybrid systems are all capable of providing electrical power for UUV. A recent study has compared their different costs and operational characteristics of power systems requiring little or no development [62].

5.5.1 Batteries

The primary challenge in assessing battery systems for UUV involves matching system voltage and current requirements to the battery characteristics for optimum performance. Figure 17, derived from [62], illustrates the problem.



$$m = \frac{I_{required}}{I_{battery}}$$

$$n = \frac{V_{required}}{V_{battery}}$$

$$V_{battery} = f\,(I_{battery})$$

Figure 17 *Array of batteries for UUV applications*

Since all batteries produce reduced output voltage with increased current draw and state of discharge to some degree, there is an interdependence of voltage and current in a given application. In addition, the energy produced by a given battery diminishes as the current flow from the battery increases, sometimes falling to as little as one half the available energy at the maximum discharge rate. The typical design approach is to arrange the individual batteries in an array as shown in Fig. 17 so that n batteries are connected in series to produce the required voltage and the m stacks are connected in parallel to produce the required current. Batteries are established products with established costs and they are very simple to use. When secondary batteries (i.e batteries that can be recharged) are used, the protective circuitry in the array must be designed to control the rate of charge in individual stacks and cells. Table 11 shows the comparison of five different cell chemistries, two non rechargeable (alkaline and lithium) also called primaries and three secondaries (lead-acid, nickel-cadmium, silver-zinc). The figure of merit used for comparison is the specific energy per unit mass specified in Wh/kg.

Chemistry	Type	Specific Energy
Alkaline	Primary	60 Wh/Kg
Lithium	Primary	440 Wh/Kg
Lead-acid	Secondary	33 Wh/Kg
Ni-Cad	Secondary	45 Wh/Kg
Silver-Zinc	Secondary	130 Wh/Kg

Table 11 *Comparison of different energy sources*

5.5.2 Fuel Cells

Because of the promise of fuel cells to efficiently produce electrical energy from chemical reactants, a considerable effort continues for their development. In the simplest representation, hydrogen and oxygen are brought together in a cell containing an electrolyte and electrons are separated from the hydrogen and flow through an external circuit while the resulting protons pass through a separator and combine with the electrons and oxygen to form water. In some cases, the separator is a solid membrane, while the hydrogen may be provided as a pure gas or derived from hydrocarbons in a reformer. Various electrolytes or cell types have been proposed and demonstrated to date, in particular Aluminum based open and closed loop systems. Off-the-shelf commercial fuel cells are becoming available for application to UUV [63] and [65].

5.5.3 Thermal Hybrid Systems

A wide variety of commercial motor generator sets are available at low initial cost. In some cases, these systems use spark ignition (SI) engines to convert hydrocarbon fuels to shaft power and in others they use diesel engines. In all cases, the engine shaft is used to drive an alternator to produce electricity. In UUV these systems run on oxygen stored as a compressed gas and the carbon dioxide produced in the combustion process is pumped overboard. With some development, turbine/alternator system can be used in place of the SI or diesel engines. The closed-cycle engines are in general quite large and do not represent a viable solution until the power required by the vehicle reaches the kilowatt level.

An analysis of the performance and cost of the different energy systems has been conducted for a large vehicle (26.5-inch diameter) capable of 300 n.mi at optimum speed [62]. Hotel loads of 500 W and 1500 W have been considered.. The different types of energy system considered in the study include closed-cycle engines (SI, turbine and diesel), fuel cells and batteries. The weight and length of different energy systems necessary to achieve a payload volume of 10 cubic ft (283 dm^3), are shown in Table 12.

Energy System	Energy Section Length (m)	Energy Section Weigth (Kg)	Payload Volume (dm^3)	Allowed Payload Weight (Kg)	Initial Cost (K$)	Total Operational Cost ($ per run)	Cost of Expendables ($ per run)
Turbine hybrid	4.67	1199.7	283	491.9	200	3570	165
SI hybrid	4.09	964.8	283	515.3	107	1630	126
Diesel hybrid	3.68	804.6	283	528.3	99	1790	91
Fuel cell	3.00	549.0	283	535.5	106	3170	172
Alkaline battery (D-cell)	2.16	533.3	283	225.0	54	7550	6800
LiSOCl2, BrCl (D-cell) (min. volume)	1.57	196.2	283	369.0	77	42,250	41,500
Li/SOCl2 (D-cell) (min. cost)	2.21	313.7	283	486.9	67	20,250	19,500
Silver/zinc rechargeable battery	1.98	397.4	283	324.0	80	4500	15

Table 12 *Characteristics of different energy systems for a 500W hotel load in a 26.5" UUV*

The initial cost reported is an estimate of the cost of purchasing a complete new energy and payload section. Total operational cost is an estimate of the cost of operating each system over an indefinite period. This cost represents the need to periodically replace an engine, fuel cell stack, or secondary battery as well as the need to replace primary batteries after each use. It also assumes that vehicle shells, structural members and gas tanks never need to be replaced. Expendables represent the cost of consumables that must be replaced after every run. They would include fuel, oxygen, primary batteries and things of that nature.

Table 13 shows unit cost data for payload weight and volume. It indicates that the hybrid diesel and spark ignition systems are particularly effective at delivering payload weight economically and that they are also superior at delivering payload volume economically. The fuel cell and turbine systems do the next best job with the difference being primarily the higher initial cost of the fuel cell stack and the turbine/alternator assembly. The primary batteries are quite expensive, exceeding the unit cost of the cheapest systems by more than an order of magnitude.

Energy system	$/kg of payload	$/dm^3 of payload
SI hybrid	3.2	5.8
Diesel hybrid	3.4	6.3
Fuel cell	5.9	11.2
Turbine hybrid	7.3	12.6
Silver/zinc rechargeable battery	13.9	15.9
Alkaline battery (D-cell)	33.6	26.7
Li/SOCl2 (D-cell) (min. cost)	41.6	71.5
LiSOCl2, BrCl (D-cell) (min. volume)	114.5	149.2

Table 13 *Cost comparison for unit weight and volume*

In conclusion, a wide variety of energy system options are available with little or no development. They have associated with them varying levels of performance, significantly different costs and operating characteristics that are unique and therefore the desired characteristics of each UUV and its operational profile should be considered carefully when choosing an energy system for it. The following specific conclusions have been drawn.

- The spectrum of cost, performance and operational characteristics of the various energy systems indicates that the optimum energy system is application dependent.

- Larger UUV tend to reduce the cost of executing a specific mission by allowing the use of less sophisticated equipment.

- Thermal hybrid and fuel cell energy systems produce low expendable and moderate operational costs when operated with gaseous reactants.

- Fuel cells appear promising as energy sources for UUV, offering higher energy than silver zinc (by a factor of two to four).

5.6 Engineering issues

Vehicle designs differ, but currently fall into two categories: hydrodynamically efficient (submarine shaped) and open space-frame (ROV-like). Many factors enter into the choice of platform design from cost and availability to compressibility of individual components; in general one must choose between an alternative that is smaller and less expensive and one that is larger with increased endurance. New ideas are being pursued in addressing the three major issues of materials, buoyancy and propulsion systems [31].

5.6.1 Materials

The weight of the vehicle must be as low as possible. To overcome this problem, developments have focused on high strength to weight materials. The use of plastic or glass-based materials for pressure hulls is an active area of development. When long endurance systems are considered, the corrosion and fouling of the platform components becomes a far more serious issue. Materials that resist such problems are required. For shallow water applications, it is very attractive the FAU design that uses modules made in composite (GRP), which can be joined together in a very simple way to create the UUV body with the required dimensions. This solution, well suited for mass production, will contribute to minimize the vehicle cost.

5.6.2 Buoyancy

The ability to control buoyancy is particularly important for AUV's that operate on a limited energy supply over extended periods of time or over extreme varying depth regimes within a single mission. The buoyancy and ballast system, for instance, must provide stability and also emergency surfacing (provide sufficient positive buoyancy to bring the vehicle to the surface during emergencies). The basic problem is that an AUV which is neutrally buoyant at the surface will likely not be neutrally buoyant at various operating depths. If necessary additional buoyancy changes can be overcome with active compensation systems, but the power consumption and reliability of those systems can become a significant factor in a long endurance mission.

5.6.3 Propulsion

The types include open propellers or shrouded propellers, contrarotating propellers, water jets, oscillating foils and controllable pitch propellers. In addition, some of these can be combined such as two contrarotating propellers mounted in tandem on concentric shafts and enclosed by a shroud. Hybrid propulsor systems can also be considered where two or more of the various configurations are installed separately on the same vehicle. Factors which impact specific design choices are efficiency, reliability, manoeuverability, complexity of fabrication and installation and torque compensation requirements. Current UUV, for the most part, rely on fairly standard technology to provide thrust and to control motion. Pressure compensated DC brushless motors turn a propeller to provide thrust and actuators move control surfaces at angles to the flow of water past the hull. These solutions are effective and have been used for years in manned submarines. Alternative concepts for propulsion and control are being considered. Larger diameter propellers or more efficient shapes are being investigated. Efforts to understand how fish are able to move so efficiently both at low and at high speeds are underway [64].

5.6.4 Launch and retrieval

Small size UUV such as *Remus* can be easily handled by two men, launched and retrieved from rubber boats. *Odysseys* and *Explorers* require a small support vessel with modest lifting capabilities (less than 1 ton crane). While *Explorer* requires a diver in the water to connect or disconnect the lifting cable to the hoisting point, *Odysseys* have been operated in the arctic directly from the support ship.

Larger UUV require a larger vessel with special launch and recovery systems. The *Hugin* system is based on a hydraulically driven cradle installed in a container positioned on the stern of the support vessel [65]. During the launch sequence the vehicle is driven out from the container and tilted down to the water. In this position the vehicle is ready to be dropped into the sea with the aid of a quick releaser. During recovery the vehicle surfaces and releases from the nose a recovery line which is grabbed from the support vessel by means of an air driven grapnel. The vehicle is then pulled back first into the cradle and then into the container. The host vessel moves forward against the wind at 4 kn during deployment and at 1-2 kn during recovery.

The deployment of AUV from submarines is usually through the torpedo tubes. For example the NMRS is loaded backwards into the SSN 688 torpedo tube and backs out of the tube under its own power. Outside the SSN (but still coupled to it *via* a steel cable and drogue assembly), it is towed to its mission area. The UUV then releases from the drogue; fibre optic cable begins to pay out from both the drogue and vehicle; and the UUV independently transits and conducts its mission. Should the optic fibre break, the UUV is programmed to autonomously return to a pre-set rendezvous point for recovery by the SSN. When the mission is finished, the UUV will rendezvous and mate with the drogue. A winch located in the SSN torpedo room will then pull the complete combination back into the torpedo tube.

The requirement that the UUV be launched through the torpedo tube imposes severe limitations to the size of the control surfaces of the vehicle, which can become unstable at low speed. Furthermore, while the deployment of the vehicle is relatively straightforward, its retrieval can be significantly more complex. Although UUV have demonstrated the capability to mate with stationary docking stations, the problem to enter a torpedo tube of a moving submarine is complicated by the flow of water around the hull of the submarine and by the poor manoeuvering capability of the UUV at slow speed which derives from the small control surfaces. For this reason mechanical drogue systems like that of NMRS are used to retrieve the vehicle outside of the submarine hull. A longer term approach is to modify the sail or the hull of the submarine to allow the installation of UUV deployment systems. This is the solution adopted by NWUC, that proposes to modify the bow of the new class SSN under development, in order to accommodate two large *Manta* AUV.

6 Conclusions

Significant progress has recently been made in the field of Unmanned Underwater Vehicles (UUV) that have reached a sufficient level of maturity to be considered as candidates for future MCM operations. Autonomous Underwater Vehicles (AUV) in particular, have the potential to perform effectively missions that otherwise would not be possible with present MCM assets. Their key advantage is the ability to operate stealthily in areas where major assets cannot go (or where they might be exposed to unduly high threat levels). The rapid development of technology will quickly overcome the remaining limitations (mainly in the field of autonomous control, energy sources and communications) and it is expected that in the first decade of next millennium, AUV will be an essential part of modern MCM system

Initially UUV dedicated to MCM applications were quite large and expensive (such as the *Draper* vehicles), but recently small and cheap units (*Remus*) have demonstrated their ability to perform specific MCM missions. Work is in progress to identify a cost effective high pay off envelope delimiting the size and cost of UUV for MCM. In recent years military, academia and industry developments have converged to medium to small size vehicles: the cost effective envelope seems to have a lower bound of 50 kg and 50 k$ and an upper bound of 1000 kg and 1000 k$.

Another issue that has received quite some attention is the amount of autonomy that a UUV should have in MCM missions. Possible approaches range from “fire and forget” strategies to an increasing level of control by means of a variety of communication links (acoustic, RF or fibre). The final choice will depend on the type of mission, but it is likely that a human operator will have to be in the loop for decisions that involve the identification and the disposal of mines. Surveillance and reconnaissance will however probably be conducted with full autonomy or limited control.

The concept of Supervised Underwater Vehicles (SUV) is attractive for a variety of situations [14]. The SUV will have sufficient intelligence and endurance to perform its mission in autonomy and to detect and classify the targets encountered. The vehicle will keep contact with its host platform by means of medium range acoustic communication that will allow the exchange of control commands, mission data and compressed images of selected targets. When longer stand off ranges for the host platform or transmission of high data rate information will be required, the vehicle will surface, or connect to docking stations, to establish RF communication *via* satellite relays. An implementation of this concept is the AOSN [6] and [7] that consists of a number of fixed and mobile nodes with sensors configured to sample the ocean and survey the sea floor with a specified resolution and precision. The mobile nodes are smart, autonomous underwater vehicles; the fixed nodes, that have acoustic and RF communication capabilities, are initially moorings and will be progressively replaced by AUV as technology progresses.

As any electrical or optical cable represents a major obstacle to remote UUV operations, the acoustic communication is considered an important technology for future UUV systems. The physics of the underwater environment and the additional problems introduced by the vehicle motion seriously limits the maximum range of transmission as well as the upper limits of data rate. Nevertheless the covertness of acoustic communication is operationally attractive for controlling an underwater vehicle and for exchanging a limited amount of information. Non-coherent modulation and frequency diversity allow to establish reliable low data rate links well suited for AUV control over short to medium distances. Recent advancements in the area of coherent modulation schemes have offered significant improvement in performance and have demonstrated the possibility to exchange compressed images at short ranges [13].

Accurate navigation over long distances will be achieved by combining high precision inertial navigation systems with DGPS and LBL fixes when available. If the operational requirement does not allow the utilization of LBL transponders or the surfacing of the vehicle to update its position, the drift of the inertial navigation system will have to be corrected by feature based navigation techniques. While aided navigation is a mature technology that can certainly provide the absolute positioning accuracy required in MCM (few metres), feature based navigation is still the subject of research [40].

The concept of modularity is common to many of the recent vehicle developments: this allows to optimize the configuration of the AUV for each mission by selecting the appropriate mix of energy, propulsion and payload sections. Acoustic, optic and magnetic payloads will be required to cover the scope of MCM missions. Sensor fusion on one vehicle, or among multiple vehicles is mandatory to reduce false alarms and keep acceptable detection performances [60].

Current MCV use forward looking sonars to detect the mine threat before they are exposed to it, or use self propelled vehicles that travel in front of the vessel. AUV however can enter the mine field without exposing human operators and expensive assets to the threat of mines; as a consequence it is feasible to detect mines by means of side scan sonars mounted on the flank of the vehicles. Furthermore the inherent stability of a slowly moving AUV is very well suited to synthetic aperture sonar processing. It is very likely that future MCM systems will utilize a combination of high (for increased resolution) and low (for penetration into the sediment) frequency SAS sonars mounted on the side of autonomous vehicles [54].

Perhaps the most fundamental limitations on realizing the more advanced UUV system concepts are the high cost and limited availability of high energy density power systems. Batteries are established products with established costs and they are very simple to use, but can provide only limited endurance (typically less than 100 km). A number of new energy systems are under development and will soon offer promising alternatives with significant increases in performance. Aluminum oxygen systems are being developed and tested by several companies. Fuel cells promise high energy densities appropriate for AUV systems, but cost and reliability factors as well as ease of use and maintenance must still be addressed.

However the rapid development of technology will overcome remaining limitations by the first decade of the next millennium when AUV will be an essential part of modern MCM systems.

7
Annex A: Definitions

1) Mine Reconnaissance: the mine countermeasure (MCM) function of determining the presence of minefields within a given region and the general characteristics of the minefields. Mine reconnaissance results can then be used to select an area of operation or a path for transit where the mine threat is small.

2) Mine Hunting: the MCM function of determining the location of each mine in a minefield. Mine hunting typically follows the reconnaissance effort and attempts to find all of the mines in the selected area so that mine neutralization (rendering the mine inoperable) or mine avoidance can take place.

3) Detection: observe an object at a level above the background noise. Detection is usually accomplished by observing a return with a signal-to-noise ratio that is 10 to 12 dB above the background.

4) Classification: determining whether the detected object has mine-like characteristics such as size, shape, or magnetic moment.

5) Identification: determining whether the mine-like object is indeed a mine. Identification is usually accomplished with a diver or an optical sensor.

6) Clutter: objects encountered by mine hunting sensors which are classified as mine-like, but are not mines. Examples of clutter include large fish, schools of fish, coral or rock outcroppings and man-made litter.

7) Volume Mines: positively buoyant mines which are connected to an anchor on the sea floor. These mines can be tethered to be near the surface, near the bottom, or anywhere in between.

8) Bottom Mines: negatively buoyant mines which lie on the sea floor. Depending on the makeup of the sea floor and the water currents, the mines may remain exposed (proud) or they may sink into the bottom and become obscured (buried). Bottom mines are the most difficult to detect when they are buried.

9) Deep Water (DW): water deeper than 300 feet.

10) Shallow Water (SW): water depths between 40 and 300 feet.

11) Very Shallow Water (VSW): water depths between 10 and 40 feet.

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A review of the applicability of UUV technology to MCM

Abstract

The emphasis on littoral warfare, the proliferation of low cost mines available to potentially hostile countries, high exercise costs and risks related to the operation of present NATO MCM units, have led to the development of Unmanned Underwater Vehicles (UUV) capable of performing a variety of operational missions. UUV may be Autonomous (AUV), or remotely operated (ROV).

The scope of this paper is to review UUV technology in the context of MCM. The operational aspects of future MCM are briefly addressed and a broad operational requirement for UUVs is proposed. Underwater vehicles relevant to MCM are examined together with some of the military and scientific programs being undertaken in the different NATO nations. UUV technology is discussed and the performance that is likely to be achieved in the near future is outlined. Two system concepts are proposed addressing covert mine reconnaissance and the detection and classification of buried mines.

UUV concepts of operation are technology limited in four important areas: navigation accuracy, communication bandwidth, robust autonomous mission control functionality and power system energy densities. Current advances in navigation are encouraging and good progress is being made in the development of compact effective navigation systems and in map based navigation techniques. Limitations in communication capabilities are being addressed by the use of fiber optic data links and by research into maximizing acoustic communication bandwidth and into advanced data compression techniques. High capacity, low cost data storage allows to complete some UUV missions without the need for on-line communication. The issue of achieving robust autonomous control for UUVs is intimately connected with progress in UUV sensor technology. Recent developments have seen the fielding of intelligent navigation, guidance and control systems and intelligent on-line mission planning systems. The high cost of high energy density power systems is however limiting the realization of the more advanced UUVs system concepts.

The review shows that UUV have reached a sufficient level of development to be considered as candidates for future MCM operations. AUV in particular, have the potential to effectively perform missions which would not be possible, except at high risk, with present MCM assets. The rapid development of technology will overcome remaining limitations by the first decade of the next millennium when AUVs will be an essential part of modern MCM systems.

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