Masterclass in AUV Technology for Polar Science

Collaborative Autosub Science in Extreme Environments

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the offshore region north of Greenland and the Canadian Archipelago – may not share the general thinning (Holloway and Sou, 2002). Satellite data has shown a continuing reduction in the area of perennial (multiyear) ice throughout the Arctic (Comiso, 2002) up to 2000, while there has been a steady decline in the total area of Arctic ice since 1979 at a rate of some 3 percent per decade, with some evidence of a recent acceleration (Parkinson *et al.*, 1999).

There are differing views on the main mechanism. One view is that enhanced bottom melt occurs through increased heat flux from a warmer Atlantic layer (Martinson and Steele, 2001; Rothrock *et al.*, 2003). Another is that a change in the basin-wide pattern of ice drift and atmospheric temperatures is the primary cause (Karcher *et al.*, 2003), reinforced by an observed rapid decrease in perennial ice fraction (Comiso, 2002), which implies shorter residence time for ice in the Arctic Basin. This decrease appears to have ceased or reversed during 2000–03 (Kwok, 2004), although data show a continuing warming of the Arctic Basin (Comiso, 2003) from the 1990s onwards, while altimetry (Laxon *et al.*, 2003) suggests a thickness variability dependent on summer insolation.

If we examine sonar profiles from prime meridian transects extending from the North Pole to the southern ice limit in the Greenland Sea, which follow typical buoy trajectories (e.g. Arctic Ocean Buoy Program, Study of Environmental Arctic Change) or streamlines of modelled ice drift, we find that a steady loss of ice occurs with a melt rate proportional to ice thickness and suggestive of an ocean-ice heat flux of some 8 $W.m^{-2}$ (Wadhams, 1992, 1997; Davis and Wadhams, 1995). The unexpected relationship was investigated by Schramm *et al.* (2000), who found no feasible thermodynamic mechanism for the thickness relationship, yet Bitz *et al.* (2001) used the CCSM2 model to predict that the thickness decrease in response to atmospheric warming is indeed greater for thicker ice via a thickness/growth feedback. Confirmatory experimental evidence of the ice melt effect on the thickness distribution is needed to determine how the latitude-dependent melt affects the freshwater flux and near-surface water structure.

The ice thinning has been accompanied by a warming of the Atlantic layer in the Arctic Ocean (Carmack *et al.*, 1997), a retreat of the cold halocline layer due to re-routing of Siberian river outflows and Bering Strait inflows (Steele and Boyd, 1998) and a change in the pattern of atmospheric pressure over the Arctic, thus of ice dynamics (Kwok and Rothrock, 1999; Yu *et al.*, 2004). The change in pressure field, and hence of ice and upper ocean circulation, have been assigned to a change of phase of the Arctic Oscillation, with the possibility that global warming induces a persistent Arctic Oscillation of a particular phase (Thompson and Wallace, 1998). Such a change inevitably alters the distribution of ice thickness and dynamics, and hence the ice flux through Fram Strait (Comiso, 2002), by affecting ice trajectories, the mean age and deformation history of the ice.

Changes in the Arctic Oscillation also affect the salinity of the upper water column through changes in freshwater storage by sea ice. The ice and freshwater fluxes in Fram Strait couple to North Atlantic thermohaline processes via the fresh water which spreads

over the Greenland Sea in summer, capping winter convective features (Budéus *et al.*, 2004, Wadhams *et al.*, 2002, 2004; Gascard *et al.*, 2002) and influencing convection in the Labrador Sea (LabSea Group, 1998). Changes are continuing and indeed accelerating; 2004 had the second smallest summer sea ice extent ever seen in the Arctic (Stroeve *et al.*, 2005) and was followed by a new record minimum in summer 2005.

3. Characteristics of Antarctic Sea Ice

Antarctica possesses a largely seasonal ice cover that has a greater winter extent – some 18 million km² – than Arctic sea ice. No significant trend in the extent of Antarctic sea ice has been found (Cavalieri *et al.*, 1997; Jacka and Budd, 1998; Ackley *et al.*, 2003), although variability on a sector-by-sector basis has been seen (Parkinson, 2002). Little information on thickness changes exists, despite the vital importance of knowing total ice volume. The absence of military submarines from the Antarctic means that only patchy information on ice thickness distribution is available. Our knowledge of Antarctic ice thickness is derived mainly from limited drilling and coring campaigns on a small number of cruises and estimates done during the passage of icebreakers.

The Winter Weddell Sea Project (1986) and Winter Weddell Gyre Studies (1989, 1992) performed systematic drilling profiles along 100 m lines at intervals of 1 m (Wadhams *et al.*, 1987; Lange *et al.*, 1989). The available data are archived under the World Meteorological Organization's (WMO) Antarctic Sea Ice Processes and Climate (ASPeCT) programme and show that the central Weddell Sea is particularly poorly sampled (Timmermann *et al.*, 2004). Ship-based sampling may in any case be biased when compared to the true thickness distribution, since ships tend to steam preferentially through thinner ice.

Further information comes from an array of six upward-looking sonars, maintained by Alfred Wegener Institute (AWI), that measure the draft of ice passing overhead. These form a line between the Antarctic Peninsula and Kap Norvegia, with a subsidiary array along the Greenwich Meridian. The sonars were deployed primarily to estimate the net freshwater export from the Weddell Gyre and thus record the draft of ice entering and leaving the gyre, rather than the ice thickness within it. They show a strong annual cycle, as the ice edge advances past and retreats back over the instruments, but give a mean ice thickness in general agreement with the drilling figures, at 0.63–0.96 m (Strass and Fahrbach, 1998; Harms *et al.*, 2001).

In winter, the first ice type to be encountered on any voyage into the Antarctic is the frazil and pancake ice that occupies the outer zone of the pack ice. This type of ice cannot aggregate to form the traditional ice sheet due to the turbulent wave-influenced environment, but is the first stage in the evolution of the winter ice cover. The presence of the frazil/pancake mixture gradually dampens the incoming ocean waves with increasing penetration, until the wave energy has dropped to sufficient levels to allow the pancakes to finally freeze together to form the more familiar pack ice. The width of the pancake zone can be up to 270 km in the Weddell Sea (Wadhams *et al.*, 1987). but is typically around 50–100 km (Doble *et al.*, 2003).

This type of ice is rarely found in the Arctic (except in the Odden ice tongue), since ice edges are typically formed from melting pack ice advected southwards (as opposed to an advancing freezing region in the Antarctic). Most measurements of the evolution of frazil and pancake ice thickness come from direct sampling methods – bringing the ice aboard with a 'pancake lifter' (Wadhams and Wilkinson, 1999; Doble *et al.*, 2003). Recent work (Wadhams *et al.*, 2004b), though, has shown the feasibility of using the changed dispersive properties of the ocean wave spectrum as it enters the frazil/pancake zone to determine the thickness of the ice cover. Clearly AUVs could provide the first opportunity to obtain a complete thickness distribution from open ocean to consolidated pack ice.

Once an ice sheet has formed from consolidated pancake ice, further thickening is largely driven by deformation (ridging) and the transformation of snowfall to meteoric ice, rather than by further thermodynamic growth (Worby *et al.*, 1998). Though many profiles of ridges have been obtained from the Arctic, ridges in the Antarctic differ markedly, since they are composed of normal ice blocks rather than crushed ice from refrozen leads.

Characteristic of the Antarctic coastal region are latent heat polynyas, sites of intense ocean-atmosphere heat loss that behave as 'ice factories', contributing a significant fraction of the total annual sea ice production. When katabatic winds open the polynya, frazil ice grows at the open-water surface, collecting at the downwind edge, with the depth of the ice layer (the 'collection depth') being a function of the ambient air temperature and wind speed (Bauer and Martin, 1983). The ice then consolidates and contributes to the entire hemispheric ice regime. Brine rejected during this ice growth is concentrated in the polynya and can cause intense localised water mass modification. Where the polynya position corresponds to an inflow of warm deep water onto the shelf, as at the Filchner-Ronne, the additional salt from ice formation can trigger or enhance the formation of dense water, essential to the maintenance of the global thermohaline circulation (Grumbine, 1991).

4. Global Sea Levels

Globally, Munk's work (Munk, 2003; Wadhams and Munk, 2004) shows that the Arctic sea ice melt rate, as measured from submarines, almost matches the rate of freshening of the global ocean determined from Levitus census studies, both being about 600 $km^3.yr^{-1}$. This allows only a small element of net terrestrial run-off and hence a small eustatic contribution to global sea level rise. If confirmed, this hypothesis requires a terrestrial sink (e.g. growth of Antarctic ice sheet) to compensate for run-off from glacier retreat, and global sea level rise predictions will be adjusted downwards. Therefore it is vital both to improve our knowledge of the present sea ice melt rate and to know where the melt water goes and what it does. Does it remain at high latitudes out of reach of current censuses? Is it having recognisable effects in altering the stability of sub-polar seas, i.e. in regulating convection in the Greenland Sea?

5. Biology

The changes that are occurring will undoubtedly be accompanied by biological effects. Already, the Barents Sea remained open during the winter of 2005–06 while it is normally frozen over during that period, and climate models predict an open Barents Sea as the next large change in the Arctic sea ice cover (accompanied by a retreat in the Beaufort Sea). This will have consequences for biological productivity, since the open southern Barents Sea is one of the most productive fishing grounds in the world, and its expansion to the north is bound to increase productivity in the newly open water. Less fortunate, however, will be animals which depend on the sea ice cover for their survival, such as polar bears and seals. Some species of phytoplankton and zooplankton, also dependent upon a habitat on or in the underside of the ice cover, will suffer change.

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Research and Development of Past, Present and Future Autonomous Underwater Vehicle Technologies

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Abstract

This chapter reviews recent developments in autonomous underwater vehicles (AUV) and their technology at Japan Agency for Marine-Earth Science and Technology (JAMSTEC), presents a number of novel concepts for manoeuvring AUVs based on bioinspiration and outlines a method using computational fluid dynamics and computer graphics to optimise AUV design.

1. Introduction

The past, present, and future AUV technologies developed by the author and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) are described in the paper. The first to be presented is the deep and long-distance cruising AUV *Urashima* powered by fuel cell, which has these specifications: 10 m length; 2.5 m width; 2.4 m height; 10 tons weight; 300 km cruising distance; 3500 m depth diving at 3 kt speed autonomously in the ocean; and is used for sea bottom surveys in earthquake areas and for research of global warming phenomena. The second AUV technology described is a marine robot designed for tasks, such as tracking plankton, installing and retrieving observation equipment, and making measurements autonomously by rapid diving down to 4200 m. Thirdly, this chapter details the bio-manoeuvring AUVs, which are fish-like swimming robots used for various purposes in scientific research. Finally, an ideal method for developing next-generation AUVs is proposed and applications are described.

2. Deep and Long-Distance Cruising AUV *Urashima*

JAMSTEC has developed the deep and long-distance cruising AUV *Urashima*, which can be used for oceanographic surveys such as sea bottom surveys in earthquake areas and the research of global warming phenomena (Figure 1). The principal particulars of the AUV *Urashima* are listed in Table 1. It is designed to have a maximum cruising range of 300 km and a maximum working depth of 3500 m, powered by the fuel cell (Yamamoto *et al.*, 2004).

Figure 1: Deep-sea cruising AUV Urashima

Length Overall	10 m	**Power Source:** Fuel cell (PEFC) and lithium-ion rechargeable battery
Width Overall	2.5 m	
Height Overall	2.4 m	
Width (Shell)	1.3 m	**Navigation Instruments:** Inertial navigation system, acoustic doppler, current profiler, acoustic homing sonar, obstacle, avoidance sonar
Height (Shell)	1.5 m	
Weight in the Air	10 ton	
Maximum Working Depth	3500 m	
Maximum Cruising Range	300 km	**Observation and Exploration Instruments:** Colour TV camera, CTDO sensor, side-scan sonar, automatic water sampler, digital camera
Cruising Speed	3 ktr	
Maximum Speed	4 kt	

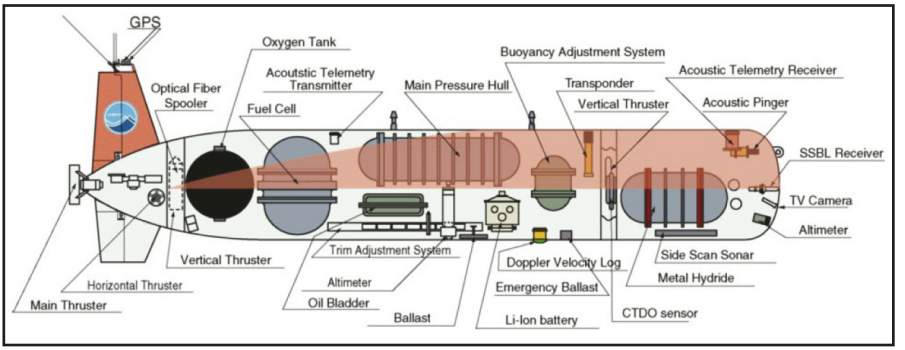
Table 1: Specifications of Urashima

Urashima is equipped with vertical thrusters, a horizontal thruster, horizontal rudders, and vertical rudders for motion control; a buoyancy adjustment system, an oil bladder, a trim adjustment system and ballast for buoyancy adjustment; and a high-performance lithium-ion battery as a secondary energy source that can be used alone for cruising to some extent. Furthermore, a digital camera and side-scan sonar are installed for precision seafloor exploration. Figure 2 shows the general arrangement of *Urashima*.

As a main power source, the fuel cell system, which has high energy density, is adapted for the AUV *Urashima*. The fuel cell for the AUV generates electricity by electro-chemical catalysis of hydrogen and oxygen. The hydrogen is stored safely within a metal hydride hydrogen-absorbing alloy.

In June 2004, Urashima successfully achieved an autonomous mission of 220 km in Suruga Bay (Tsukioka *et al.*, 2004). It made four roundtrips between transponders spending 44 hours submerged. In the February 2005 sea trial, *Urashima* achieved an autonomous long-range cruise to the world record of 317 km for a fuel-cell powered AUV (Yamamoto, 2005a).

Figure 2: General arrangement of Urashima



3. Working AUV *MR-X1*

While *Urashima* is designed to collect oceanographic data and water samples autonomously over a large area of the ocean, a marine robot *MR-X1* is being developed as a working AUV for the scientific work of tracking plankton, installing and retrieving observation equipment, and measuring sea data autonomously by rapid diving (Yoshida *et al.*, 2004).

Table 2: Specifications of MR-X1
(feature to be installed)*

Weight	800 kg (in the air)
Dimensions	2.55 (L) x 0.8 (W) x 1.2 (H) m
Working Depth	4,200 m
Cruising Speed	2 knot
Working Time	15 hours and more
Operation Mode	Wireless / autonomous
Working Tools	TV camera, side-scan sonar, robot hand*, CTDO*

The principal particulars of the working AUV *MR-X1* (Figure 3) are listed in Table 2. The shape is like a headfish[1] to reduce hydrodynamic drag in decent and ascent (Figure 3). The AUV requires a system platform with specifications of high-speed response, compact software program, small size, low power and high redundancy. Therefore, we developed a simple distributed processing system for the *MR-X1* with multi-microprocessor boards combined with controller area network (CAN) bus. The control system platform for the *MR-X1* consists of a main processor board (controller) and sub processor board (target). As a new central processing unit (CPU) board for the controller for further improvement, the Renesas SH4 microprocessor with CAN bus was

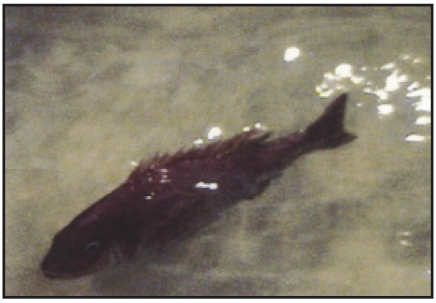
Figure 3: Marine Robot MR-X1

[1] *Mola mola* – ocean sunfish

selected. Its operating system is iTRON, which is a Japanese real-time OS having advantages over common operating systems and has been used in sea trials.

A sea trial of the MR-X1 without a manipulator and side-scan sonar took place in Suruga Bay in November 2003. The MR-X1 dived autonomously, and we could observe the state of affairs in the sea visually, obtaining fruitful data for further improvement in June 2005. In the near future, this AUV will be able to recognise images of a target for various robot manipulator tasks in the sea.

Figure 4: Bio-manoeuvring underwater vehicle swimming in the water and (left) its internal structure (right)



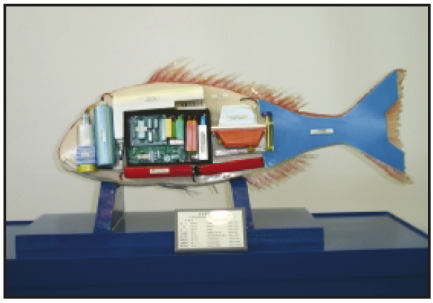


Figure 5: Internal structure of flat fish robot prototype (left) and the external appearance of flat fish robot prototype (right)

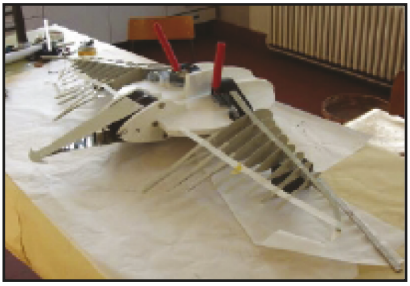
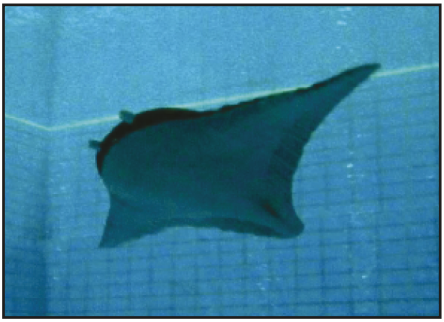
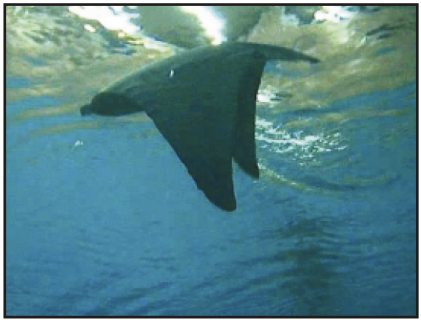


Figure 6: Swimming (left) and somersault (right) of the flat fish robot





4. Development of Bio-Manoeuvring Underwater Vehicles

Bio-manoeuvring-type underwater vehicles (fish robots) have been developed for needs related to mineral resources, ocean structure maintenance and environmental measurement. These underwater vehicles are propelled by 'fin' movement, like fish and other aquatic life (Yamamoto, 2005b). Utilising the latest dynamic system theory and mechatronics technology, a flexible oscillating fin propulsion system was built to realise flexible movement of fish. Furthermore, advanced autonomous control logic was developed to create a lifelike swimming fish robot capable of three-dimensional autonomous movement without cables. Figure 4 shows the appearance of the developed underwater vehicle (swimming in the water) and its interior.

A prototype flat fish robot was also developed for high-efficiency resource exploration with less energy loss, as well as for minimal disturbance and smooth landing on the seabed for resource collection. This work is aimed at building an underwater vehicle with flexible oscillating wings that can move smoothly based on the principle of wing flapping. Figure 5 shows the interior of the prototype and its exterior appearance. Figure 6 shows the flat fish robot swimming and performing a somersault, demonstrating its flexibility.

Further research on the bio-manoeuvring-type robot will produce a wide variety of technologies for the development of ocean instruments, as shown in Figure 7.

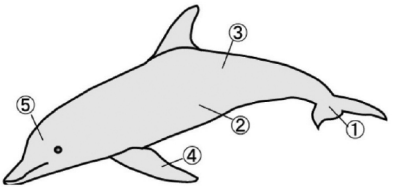


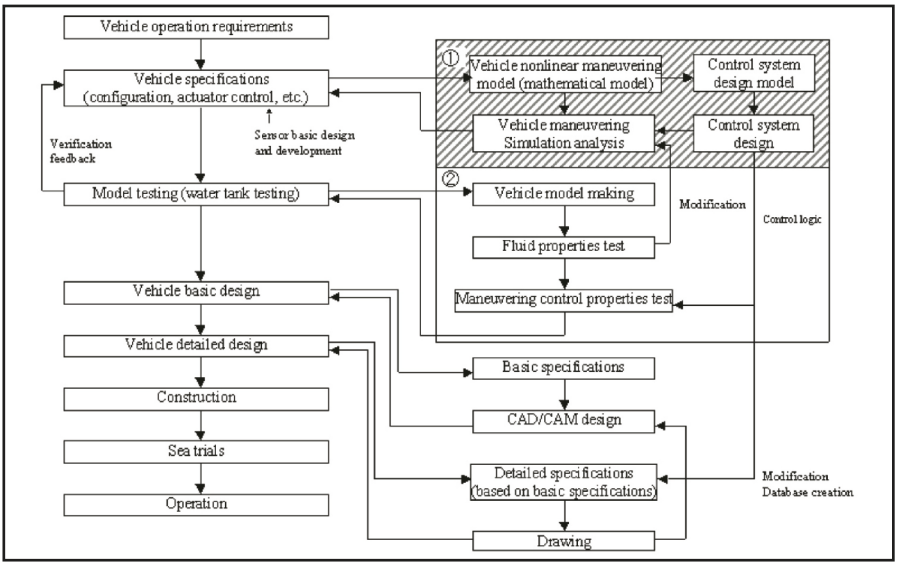
Figure 7: Technologies produced by bio-manoeuvring-type robot research

Research issues	Technologies to be produced
1) Thruster: Flexible oscillation fin propulsion system	- Environmental friendly actuator without stirring - Actuator with no calibration, high instantaneous force, forward/backward switch, and excellent turning - Auxiliary actuator with propeller (backup in case of failure) - Robot hand able to hold objects of any shape gently
2) Body: Optimum configuration design	- Design of configuration and skin with minimum drag force - High-efficiency maneuvering vehicle using body flexibility
3) Material: New materials	- Flexible, pressure-proof, soundproof, waterproof, and high workability materials, environmental friendly renewable materials - Able to be widely used as underwater material
4) Fin: Soft landing, launching and turning system	- System for soft landing and object collection at seafloor target area - System for smooth movement with soft launching and turning
5) Sensor: Bionic sensor	- Fisheye multidirectional sensor, dolphin-shaped acoustic sensor able to detect the thickness of an object - Used as warning object alarm - Used generally as underwater sensor
* Overall: Future underwater vehicle	- Aquatic bio-maneuvering control equipment - Able to move at narrow space, softly and quietly - Used for bionic logger and resource exploration (collection equipment)

5. Ideal Method for Developing Underwater Vehicles

Figure 8 shows the ideal method devised in this project for developing underwater vehicles. As shown in the flowchart on the left side of Figure 8, the underwater vehicle development process includes: definition of vehicle specifications, such as configuration, actuator, control and sensors in accordance with operational requirements; water tank testing of the model for performance verification; and feedback comparing the verification results with the defined specifications. The important processes, which this project focused on, are the simulation design process – (1) in the flowchart on the right side of Figure 8 – and the model-making process followed by the fluid properties test and manoeuvring control properties test – (2) in the flowchart. Model testing through the above processes can identify necessary refinements at an early stage, before construction of the vehicle, and thereby facilitate the process of basic design, detailed design and construction of the vehicle afterwards. By adopting this method, the risk of reconstruction and major modification after construction of the vehicle can be reduced to minimise the overall development risk.

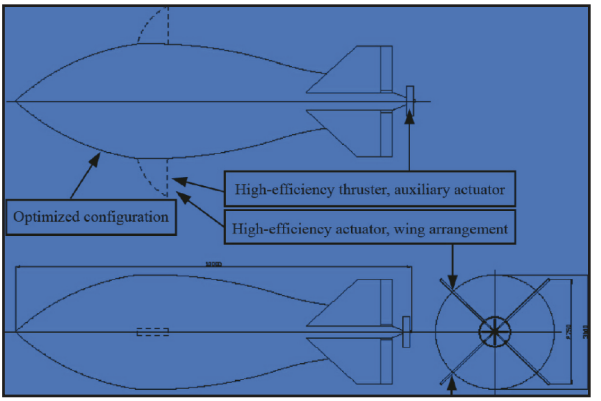
Figure 8: Ideal design process for developing underwater vehicles



6. Development of Next-Generation Unmanned Underwater Vehicles (UUV)

Figure 9 shows a layout of the vehicle proposed in view of the challenges outlined in Section 5. The key technologies are the optimisation of vehicle configuration using computer fluid dynamics (CFD) and the control system to ensure fail-safe operation. The vehicle has an X-shaped tail (as shown in Figure 10), which features high capacity lift, high lateral force, high manoeuvrability, smooth berthing and storage, and easy system backup in case of wing failure. The X-shaped tail of the developed model can be changed to a conventional cross-shaped tail and vice versa.

Figure 9: Layout of new underwater vehicle



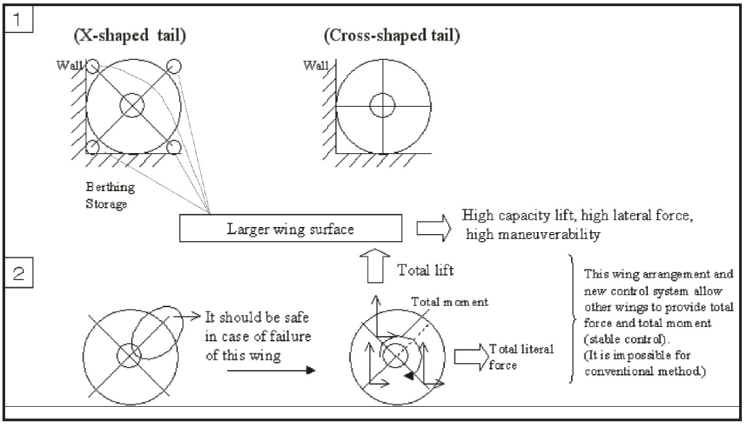
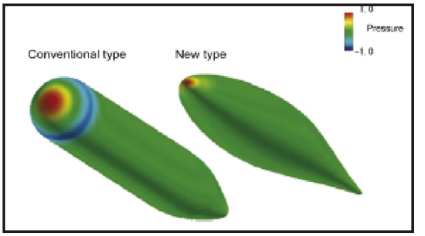
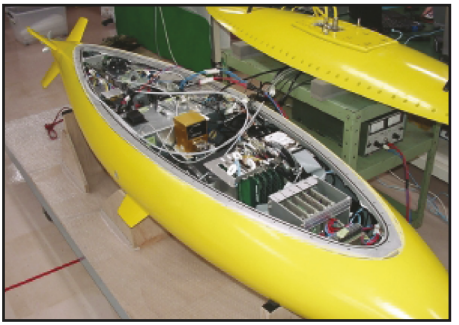
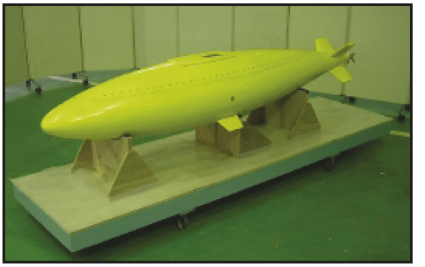


Figure 10: Features of X-shaped tail (left)

Figure 11a, 11b and 11c: (11a, right) Optimum vehicle configuration from CFD simulation and (11b, below right) the model (11c, directly below) with internal structure



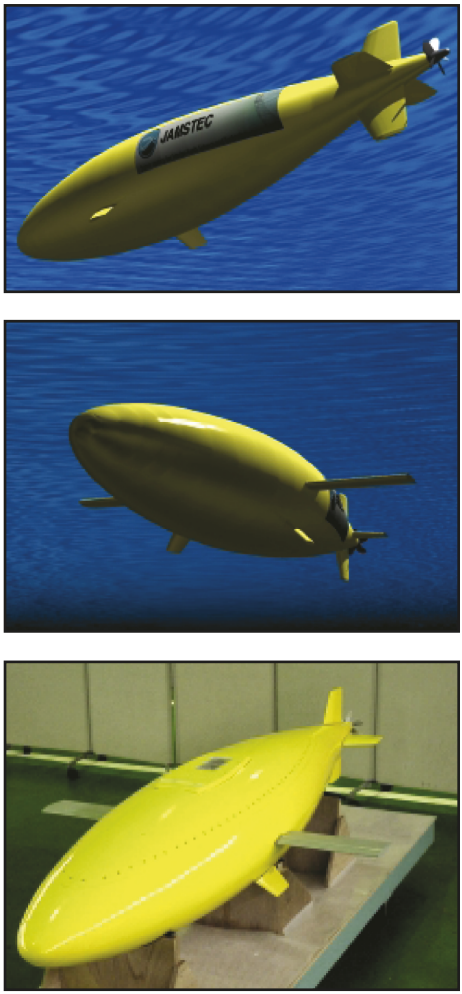




The optimum vehicle configuration was simulated using CFD based on Reynolds-averaged Navier-Stokes equations, whose simulation results are shown in Figure 11a, 11b and 11c. In Figure 11a on the left is a conventional cylinder shaped vehicle, while on the right is a new configuration designed to provide uniform surface pressure distribution (indicated by the same colour in the figure). Small pressure fluctuation will result in reduced flow turbulence and hence minimum drag force. Figure 11b shows the appearance of the model constructed from the simulation results, and Figure 11c shows its interior. The model is 2.6 m in length, 0.5 m in maximum width, and 0.4 m in maximum height. It is equipped with a lithium battery, ballast tank, motion sensor and control system to operate autonomously without cables.

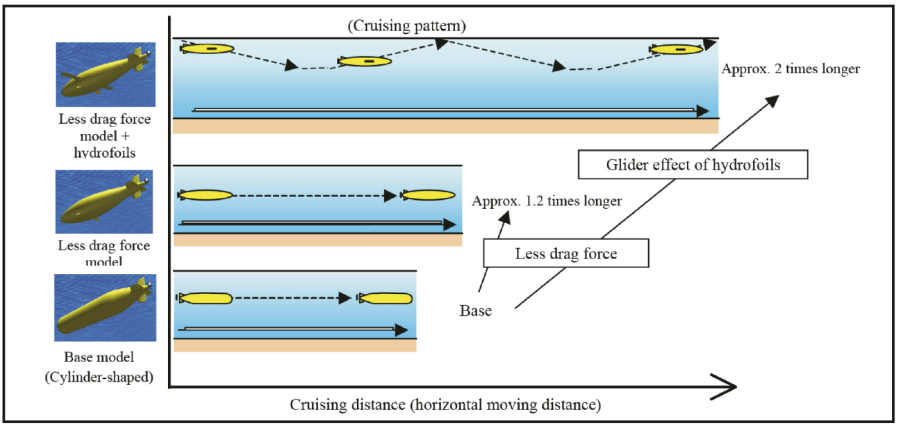
A technique was also developed to use computer graphics to design a vehicle from computer-aided design (CAD) data used for the model construction. Figure 12a shows the model designed by computer graphics, while Figure 12b shows a model designed by computer graphics to have hydrofoils for optimum lift. Based on the computer graphics data, the model was constructed as shown in Figure 12c. The manoeuvrability of the conventional cylinder-shaped model and the optimum configuration model (with/without hydrofoils) were verified by water tank testing. The test results are shown in Figure 13.

Figure 12a, 12b and 12c: (12a, top) Model design by computer graphics (12b, middle) underwater vehicle with hydrofoils designed by computer graphics (12c, bottom) model with hydrofoils



The water tank testing and analysis indicates that the next-generation model has a considerably longer cruising distance than the conventional (cylinder-shaped) type because of the glider effect of hydrofoils and less drag force, as shown in Figure 13 (evaluated at constant body length and energy). The glider cruising has the advantage of extending the cruising distance, especially by using its own lift forces.

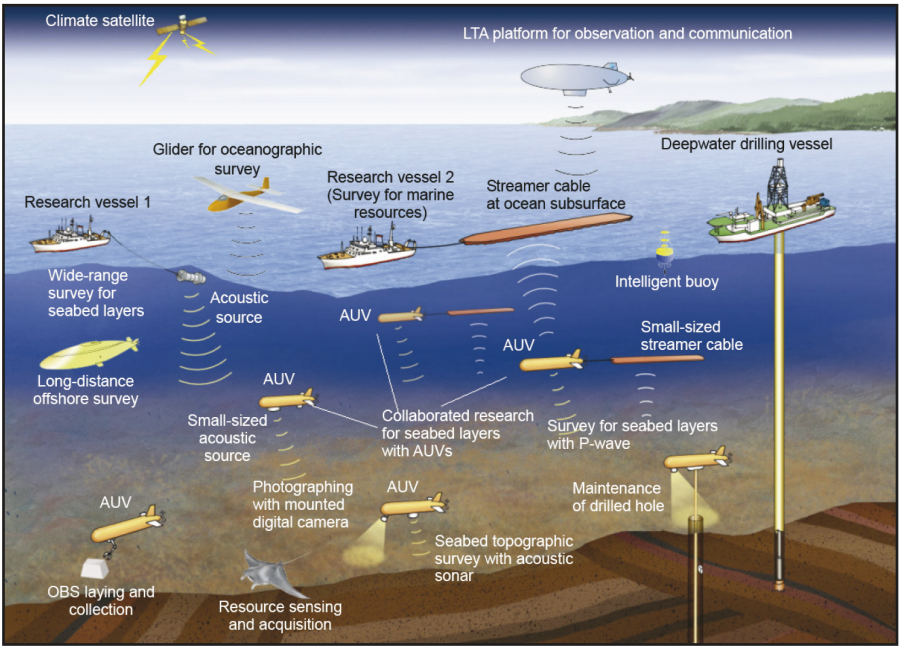
Figure 13: Comparison of cruising range between next-generation and conventional model



7. Final Remarks

The author envisages a marine system network based on AUVs in the future. The concept is illustrated in Figure 14. The system is expected to realise sustainable development of the ocean and to produce prosperity for human beings. Also, the author wishes to make a contribution to realise a worldwide marine system network based on AUVs by international cooperation.

Figure 14: Next-generation marine systems network



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Autosub Operations in the Arctic and the Antarctic

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Abstract
Autosub is a 3600 kg, 6.7 m long autonomous underwater vehicle (AUV), with a 1600 m operating depth and range of 400 km. It was designed, constructed and is operated by engineers at the National Oceanography Centre, Southampton. Between 2001 and 2005, as part of the UK Natural Environment Research Council (NERC) funded scientific research, we took Autosub on five expeditions – three in the Antarctic and two in the Arctic. Autosub executed a wide variety of missions, including assessment of krill populations underneath Antarctic sea ice; the measurement of sea-ice thickness and iceberg draughts; conductivity, temperature and depth (CTD) and acoustic doppler current profiler (ADCP) measurements under sea ice; and finally, measurements of oceanography, biology and glaciology under an Antarctic ice shelf. There were a wide variety of technical problems to overcome. While most missions require good navigation accuracy, compasses and gyros are compromised by high latitudes. To cope with collision hazards, be they due to sea ice ridges, icebergs or the ice shelf environment, we developed a collision avoidance system and associated algorithms. Due to the ever-shifting sea-ice, a homing system to shepherd Autosub back to a safe recovery position was developed. This paper will describe the achievements of Autosub during these polar operations, with particular emphasis upon the technical difficulties that we came up against and the solutions we adopted in solving them.

1. Introduction

The first Autosub polar mission was in the Antarctic in 2001, but this was a culmination of a development effort stretching back twelve years. In 1989 the idea for Autosub was first conceived of by engineers and scientists at the Institute of Oceanographic Sciences* (McCartney and Collar, 1989; Collar and McPhail, 1995). Funded by NERC, the first Autosub vehicle, *Autosub-1*, was constructed in eight months and, following completion in April 1996, was launched within the confines of Empress Dock, Southampton, for a series of engineering trials. During the next few years, the capabilities and autonomy of the vehicle were gradually increased (Millard *et al.*, 1998).

In 1999, Autosub began an 18-month, NERC-funded thematic programme, 'Autosub Science Missions'. This programme provided very valuable experience of operating Autosub within a wide variety of environments and with a multitude of different sensors (Millard *et al.*, 2003). Highlights of this programme were mapping the flow through the Strait of Sicily (Stansfield *et al.*, 2001); use of a flow cytometer to identify plankton in the English Channel (Cunningham *et al.*, 2003); assessment of herring stocks in the North Sea (Fernandes *et al.*, 2000); and use of novel chemical sensors in Scottish sea lochs (Overnell *et al.*, 2002). During this programme, particularly during the North Sea and the Strait of Sicily campaigns, operation of Autosub 'over the horizon', well beyond the range of its acoustic tracking and communications system (4 km), for periods of 24 hours or more, became very much the norm. Autosub was routinely operated in purely autonomous mode, while the mother ship carried out other operations.

As part of this programme, we first gained our experience of operating Autosub in a polar region. In February 2001, hosted on the RRS *James Clark Ross*, we operated Autosub near and under sea ice in the Weddell Sea, Antarctica. In addition to the standard suit of navigation and control systems, Autosub was equipped with a Simrad EK500 scientific echosounder operating with 38 and 120 kHz transducers. The two frequencies were used to distinguish the target species (Antarctic krill – *Euphausia superba*), from other zooplankton. Six missions were run, a total of 100 km under sea ice, with the Autosub running at constant depths of 80–120 m, and with the echosounder looking upwards towards the underside of the sea ice. Using this data, it was possible to demonstrate that the krill were more abundant just within the boundary of the sea ice, than in either open water or further into the sea ice (Brierley *et al.*, 2002). EK500 sensors are large (600 mm diameter for the 38 kHz acoustic transducer), and the transceiver and data logging system in their pressure case weighed 105 kg in air (humorously known as the 'Behemoth'). This illustrates a benefit of a large AUV such as Autosub; bulky sensor systems can be accommodated with relative ease.

As well as providing several high calibre science papers for the principal investigators, this campaign also gave the technical team a great deal of very valuable experience and

* Later absorbed into the National Oceanography Centre, Southampton (NOCS)

data for Autosub when operating in polar regions. For example, in subzero, blizzard conditions, at times it became obvious – through the pain of freezing fingers and the difficulty of keeping equipment dry – that for future campaigns, we would need to provide a warm, dry area for working on the vehicle and changing the batteries (~5000 alkaline manganese D-cells). Future polar campaigns would use two modified, heated, 20-foot shipping containers.

We also obtained valuable acoustic data from our forward-looking echosounder (a Simrad Mesotech 200kHz unit) and the upward-looking 300 kHz ADCP. Prior to this campaign, we had very little information on how well the ADCP might work when tracking the underside of sea ice, or the underside of an ice shelf. Of course, we were not able to run the Autosub under an ice shelf during this campaign, but we were able to find the next best thing, a piece of broken-off ice shelf (an iceberg). It took several attempts to navigate the Autosub under an iceberg (driven by winds and currents, icebergs can move unpredictably and surprisingly fast, and a moving target is harder to hit), but we eventually were able to acquire the data we needed. We successfully measured the draught of the iceberg using the four beams of the upward-looking ADCP (up to 170 m in this case), and demonstrated that it was possible to measure the velocity of the AUV relative to the iceberg. False triggering of the forward echosounder by shoals of krill was a problem, necessitating the development of more sophisticated algorithms for detecting hazards (e.g. icebergs), with an acceptably low false alarm rate.

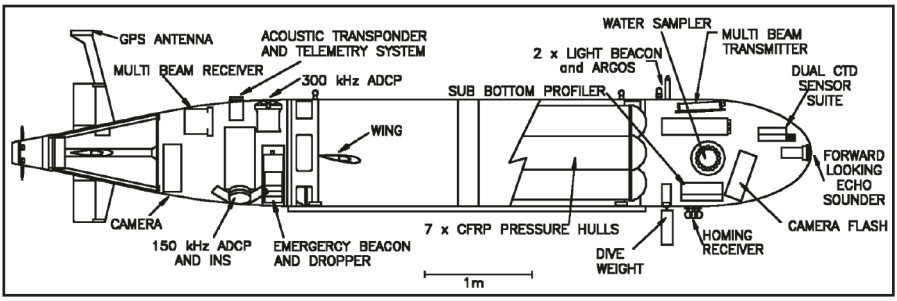
During this campaign we had our first experience of the dangers of icebergs to AUV operations in polar regions. Toward the end of mission 252, without any effective collision avoidance system, the AUV was blind to an apparently small (but with a draft of over 150 m) iceberg that drifted between the Autosub and its recovery position. The Autosub hit the iceberg a glancing blow, causing damage to the vehicle's nose-mounted communication transponder. Fortunately the control and propulsion system continued to operate and the vehicle skidded and bumped along the underside the iceberg, emerged on the other side and continued onto the recovery position. Future campaigns would clearly require the development of a collision avoidance system able to cope with icebergs, and later the under-ice shelf environment.

2. The 'Autosub Under Ice' Programme

In 2001 NERC awarded funding for the 'Autosub Under Ice' (AUI) programme, a five-year programme to utilise Autosub to investigate the nature of physical and biological processes beneath polar ice. The most challenging objective of this campaign was to send Autosub deep under an ice shelf in the Antarctic, and to make measurements of the biology, chemistry, glaciology and morphology of this totally unexplored region. It was clear that some substantial changes and improvements would be needed to the basic Autosub vehicle in order to cope with the challenges presented by this environment and to integrate new sensor systems. We started a two-year programme of

development and testing. All-at-sea testing was carried out using the MV *Terschelling* dive support ship, either in coastal areas of the English Channel, or the deeper waters of the South West Approaches. Figure 1 shows the configuration of the *Autosub2* vehicle for the AUI programme.

Figure 1: The major systems of Autosub2 *and science sensors that were developed, integrated and tested between the end of the Autosub Science Missions programme in 2001 and the first mission of the AUI programme in 2003. The vehicle is 6.7 m long, displaces 3.6 tonnes and has a range of 400 km at 1.7 m.s* $^{-1}$ *with the sensors shown*



2.1 The Navigation System

The two primary sensors for the navigation system are a 150 kHz Teledyne RDI ADCP and Ixsea-Oceano PHINS fibre-optic gyro-based inertial navigation system (INS). To get best accuracy (performance of 0.1 percent of distance travelled was typically achieved, even at latitudes as high as 80 degrees North), the downward-looking ADCP must be able to bottom-track the seabed. The mission profiles for the under-ice-shelf work necessitated as far a bottom-tracking range as possible. This meant that we had to use the lower frequency 150 kHz ADCP (with a bottom-track range of 500 m) rather than the 300 or 600 kHz systems (which only give 200 and 100 m, respectively) more typically employed by AUVs. The effect was the need to accommodate on the vehicle a much bulkier ADCP transducer. Both the INS and the 150 kHz ADCP were housed within a single pressure case. The advantage of this arrangement was that the all-important mechanical alignment between the ADCP and INS could be accurately maintained between missions*, requiring that the alignment to be measured once only.

The navigation system was also able to utilise the velocity tracking data from the upward-looking 300 kHz ADCP. This would be used when the Autosub was flying within a cavity under an ice shelf, close enough to obtain useful velocity tracking data from the underside of the ice shelf (less than 150 m range), but too far from the seabed to use the

* For a misalignment angle θ uncorrected, the cross track velocity error is $s.\sin\theta$ where s is the forward speed of the vehicle. On integration, the velocity error becomes a distance error.

(preferred) bottom tracking mode. The upper ice shelf is suitable as a reference for velocity measurement because, for our practical purposes, it is stationary. Sea ice is less useful for this purpose because it is often drifting at significant speed relative to the speed of the AUV. This caused a problem for us during early undersea ice missions in deep water. Because bottom-tracking was not possible, and the upward-looking ADCP had acquired velocity tracking from the sea ice, the navigation algorithm selected the upward-looking tracking for the velocity source, thus causing a navigation drift rate equivalent to the (mostly wind driven) drift rate of the sea ice (Griffiths *et al.*, 2003).

For later campaigns, the algorithm was changed so that sea ice and shelf ice could be effectively discriminated. The algorithm estimated the thickness of the ice, which is simply the vehicle depth (measured by the Digiquartz pressure transducer) minus the acoustic range to the target above (measured by the upward-looking ADCP beams). For ice thickness estimated at more than 20 m, the surface was considered to be stationary for the purpose of navigation.

2.2 Homing System

The rationale for a highly accurate navigation system was that when executing under-ice missions, we might require the vehicle to travel 100 km or more without the possibility of global positioning system (GPS) fixes, or tracking from the mother ship. We would also require it to navigate its way back to a hole in the ice or polynya, which might be only a few hundreds of metres in extent. However, on occasions, due to drifting sea ice conditions, it may not be possible at the time of launch to be certain that the recovery position would be clear of ice.

Furthermore, we needed to be able to cope with the situation when the mother ship could not get to the intended recovery position, or when unexpected navigation system drift or some other system failure, could leave the AUV still operating a long way off from the intended recovery position. Recognising these possibilities we embarked on the development and testing of a homing system able to shepherd the Autosub back towards the mother ship at ranges of up to 15 km. The system consists of a transmitter at the mother ship that emits regularly spaced swept frequencies (chirps), centred at 4504 Hz. The acoustic projector is lowered on a cable down to a depth of up to 100 m. On the vehicle are three spherical hydrophones (see Figure 1), together with a digital signal processing (DSP) based three-channel correlation receiver, and they allow the determination of the direction of arrival of the homing signal. Once the system has detected four consecutive transmissions with the correct temporal spacing, the AUV enters homing mode and heads towards the source of the signal.

2.3 The Collision Avoidance System

The collision with an iceberg during the Autosub Antarctic campaign of 2001, and the realisation of icebergs, ice ridges, and the under-ice-shelf (by its nature appreci-

ably unmapped) collision hazards, led to the decision to develop a strategy, system and algorithms for collision avoidance, specifically tuned to the polar operations. The system relied upon use of sensors and data already available to us on the vehicle: the depth sensor, the four upward-looking ADCP beam ranges, the four downward-looking ADCP beam ranges and the forward-looking echosounder (a 120 kHz Simrad Mesotech echosounder). The paradigm was to keep things as simple as possible, to trigger one simple yet effective behaviour upon the system detecting whether a collision was imminent.

Collision avoidance mode is entered if the forward-looking echosounder detects an object continuously closing on the vehicle at range less than 100 m, or if there is less than 50 m depth of water for which the vehicle to operate safely (measured in the simplest case by the upward- and downward-looking ADCP ranges, but also taking into account safe limits for vehicle depth). Once collision avoidance mode is triggered, the vehicle backtracks for 1 km along its previous track. It then is turns back along its original route, but with an offset of up to 500 m to its track, so that it has a greater chance of avoiding the hazard. It also adjusts its depth safety limits, to increase the margin of safety in the vertical direction. If an imminent collision is detected again, the vehicle repeats the collision avoidance manoeuvre, but with a difference track offset. Once clear of the obstacle, the original course and safety limits are restored.

Both the homing system and the collision avoidance system proved their worth in the first cruise of the 2004 Arctic campaign, in particular during Autosub mission 365. The mission was planned was to start in open water, and then run 72 km west at 40 m depth, under the fast ice and towards the Northeast Greenland coast, while measuring the thickness of the ice using the upward-looking multibeam echosounder (Wadhams *et al.*, 2006).

The outward journey proceeded without incident, and 12 hours into the mission the vehicle turned and headed back along the reciprocal track (Figure 2). However, 120 km

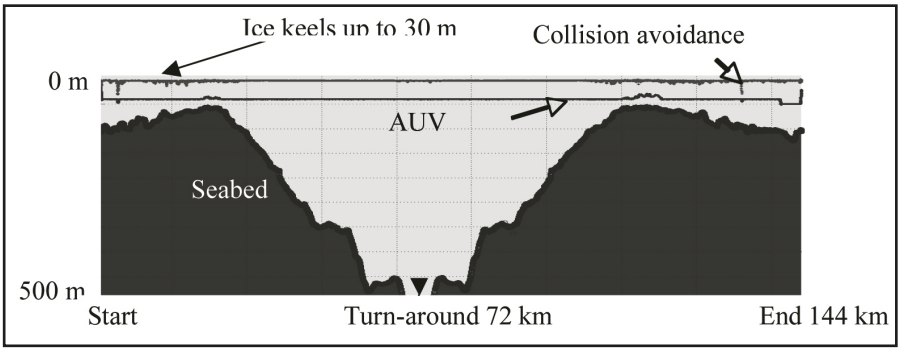


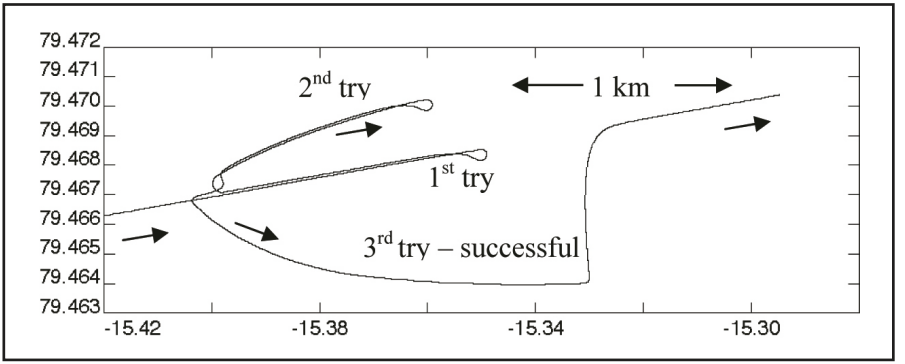
Figure 2: The depth profile for Autosub during mission 365, operating off the Northeast Greenland coast. The upper trace is the ice draft (obtained using the upward-looking ADCP beams), the lower trace the seabed (from the downward-looking ADCP)

into the mission, the collision avoidance behaviour was triggered. The Autosub travelled in for 72 km under the fast sea ice and then out for 72 km (hence the symmetrical plot of seabed depth, based upon the vehicle ADCP ranges in Figure 2). In places the Autosub had to alter its depth to keep a safe distance away from the ice and seabed boundaries. Towards the end of the outward leg, the AUV was forced to execute collision avoidance behaviour in order to avoid a 30 m ice keel.

Figure 3 shows the plan view of the collision avoidance behaviour, as recorded by the vehicle navigation system. The vehicle successfully avoided the ice keel hazard at the third attempt. However, the troubles were not over for the Autosub. Although the planned recovery position was clear of sea ice at the time of launch, at the time for recovery – 24 hours later – the wind had changed direction, to blow from the east. Thus it had pushed pack ice over the intended recovery position, making recovery unsafe there. Fortunately, we anticipated this possibility; rather than immediately surfacing at the end of the mission, we had programmed the vehicle to circle indefinitely at a depth of 50 m at the nominal recovery position. This gave us the opportunity to position the ship in clear water (4 km away), to lower the homing system transmitter, start transmitting and shepherd the vehicle towards clear water. We monitored the position of Autosub using the ultra short base line system (ORE TrackPoint II). With the Autosub 400 m short of the ship and in safe ice-free water, the acoustic command was sent for the Autosub to surface.

This mission, and others like it during the north Greenland AUI campaign of July 2004, have provided a unique insight into the underside of sea ice, imaged using the EM2000 multibeam system, looking upwards (Wadhams *et al.*, 2006).

Figure 3: Plan view (latitude, longitude) of collision avoidance behaviour, triggered by detection of a 30 m deep ice keel ahead. It took three attempts for the Autosub to avoid the hazard



2.4 The Emergency Beacon System

If the Autosub systems detect a critical failure, or if there is a catastrophic power failure during the mission, an emergency beacon system starts transmitting once per minute a

4.5 kHz chirp. Simultaneously, the acoustic projector is dropped on a 15 m cable from Autosub (Figure 1), to give it clearance of any ice keels or ridges that might otherwise obstruct the acoustic signal. The ship-based receiver shares transducer hardware with the homing system, a vertical array deployed to a depth of up to 100 m. By timing the arrival time of the received signal, it is possible to triangulate the position of the Autosub by moving the position of the receiving ship. The range of the system is up to 30 km, given a suitable acoustic path.

2.5 The Camera System

One of the first questions that people almost always ask when introduced to an AUV such as Autosub is, "Does it have a camera?" Photographic images of seafloor flora and fauna have an appeal that is immediate and exciting. In practice for many mission profiles, a camera would not be useful because the AUV mission profile does not take it close enough to the seafloor (maximum about 10 m) to get satisfactory photographs. However, as part of the AUI programme, there was a requirement to photograph the seafloor undersea ice or ice shelves (Jones *et al.*, 2005).

Technically, the problem is to devise a system that has the required performance (a resolution of 1.5 mm on the seafloor), while the vehicle flies at a safe altitude for the seafloor conditions. In regions known to be fairly flat, we took the minimum safe altitude to be 10 m. This immediately ruled out colour photography because only the blue end of the spectrum would have sufficiently low attenuation over the 20 m roundtrip. There not being a commercial solution, we developed our own system based upon a high sensitivity, Peltier cooled, monochrome CCD sensor – the Startlight SXV-H9 – intended for use by amateur astronomers. This use the Sony ICX1285AL Exview HAD CCD, with 1396 x 1040 6.8 µm square pixels. A Minolta 3600HS zoom flash, housed in a windowed pressure case, provided the illumination. Integrated into the vehicle control LonWorks network, it was relatively simple to arrange that photographs were only taken with the vehicle at the correct altitude (less than 12 m). Figure 4 shows an Autosub camera image taken from an East Greenland coastal area.

3. Mission 382 and 383 – The Final *Autosub2* Missions

The final successful mission, 382, of *Autosub2* was on 13 February 2004 (Figure 5). This was the first time that an AUV had run successfully under an ice shelf. The objective was to measure the oceanographic conditions within the ice cavity (conductivity, temperature, oxygen, currents from upward- and downward-looking ADCP), as well as the morphology of the seabed (using the downward-looking ADCP) and detailed mapping of the underside of the ice shelf (using the EM2000 200 kHz swath bathymetry system, looking upwards, as in Figure 1).

We launched just outside the ice shelf and, as planned, the vehicle circled at depth while we uploaded engineering data from the vehicle over the acoustic link. When satisfied that everything was normal, we sent an acoustic signal to command the vehicle to

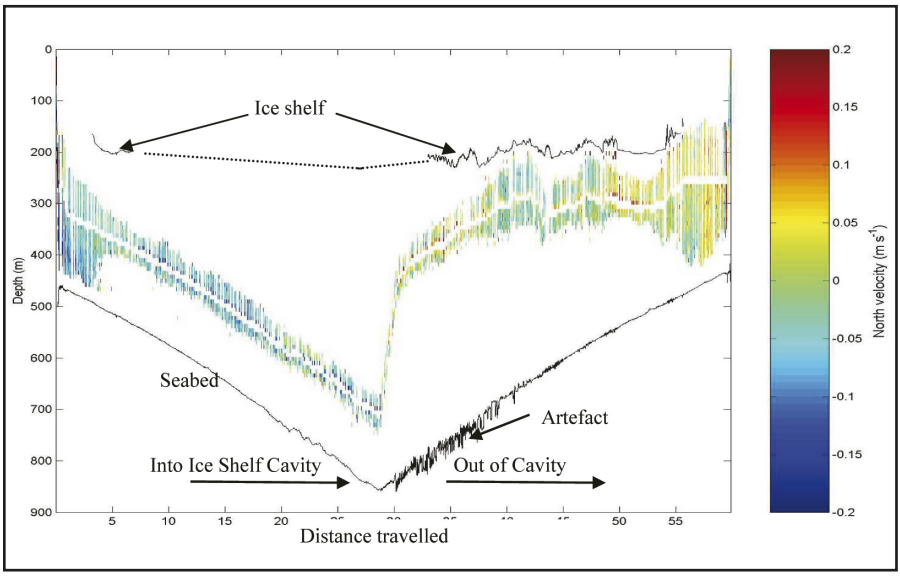
Figure 4:
This Autosub image from Greenland covers 2 m x 1.6 m, taken from an altitude of 10.4 m at a depth of 570 m at 68.0264 degrees N 31.8057 degrees W, heading (up) 38.0 degrees

progress under the ice shelf. The vehicle tracked the seafloor at an altitude of 150 m, until it was 22 km under the ice shelf, then it turned back on a reciprocal track, this time flying at constant altitude of 400 m. Having progressed 10 km, the altitude demand was changed to 300 m, and the vehicle progressed with this demand until it had cleared the ice shelf. The reason for these depth changes was to ensure that the return leg was as safe as possible, given the relatively crude information we had about the ice draft (based on a seismic survey carried out several years previously), and for the vehicle to operate in bottom-track mode as long as possible. (Although use of the ice shelf as a reference for navigation was possible, as described earlier, for this preliminary mission into an ice cavity it was desirable to use only tested modes of navigation.)

The mission was highly successful, generating a unique data set of physical and chemical measurements under the ice shelf. The multibeam imaging of the underside of the ice shelf was particularly interesting, showing many deep ridges in the ice and a surface roughness that was much higher than was previous considered to be the case. This had significance for the calculation of the hydrodynamic drag coefficient for the base of the ice shelf, and hence the flow within the ice cavity (Nichols *et al.*, 2006). Note the

decrease in ADCP range within a short distance of entering the ice cavity in Figure 5. The hypothesis is that this was due to fewer and or smaller zooplankton scatters within the cavity.

Figure 5: Track of Autosub into and out of the Fimbulisen ice shelf cavity. Tracking of the ice shelf was on the return track, when the vehicle was close to the ice shelf. The ADCP north component is shown – Courtesy of Keith Nichols and Povl Abrahamson (British Antarctic Survey) and Kate Stansfield (NOCS)



Mission 383 was planned to run on a similar track to mission 382, the main difference being that the vehicle would profile to within 50 m of the ice shelf base and the seabed on the outward leg and follow the base of the ice shelf at range of 100 m on the return leg. Unfortunately, transmissions from the emergency beacon system, emanating from a position 15 km under the ice shelf, indicated the Autosub was stranded, most probably (as the acoustic signal was strong, indicating a clear acoustic path) floating against the ice shelf. Given its position, there was little hope of successful recovery. A thorough analysis was carried out into the likely cause of the loss, but due to lack of detailed telemetry information, it can only be expressed in terms of probabilities. The single most likely cause is a system power failure, as a result of some unknown hardware or connector failure (Strutt *et al.*, 2006).

Following this loss, the replacement vehicle, *Autosub3*, was successfully tested four months later, in June 2004. Some design changes had been rapidly implemented to eliminate some of the weaknesses and vulnerabilities in the system that had been identified by the loss review. In July and August 2006 *Autosub3* carried out a series

of long range, long duration (up to 60 hours) missions in the Northeast Atlantic and the Irish Sea, carrying a flow cytometer and a turbulence probe respectively. The successor to *Autosub3*, the 6000 m rated *Autosub6000*, is scheduled for deep-sea trials in September 2007.

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Sensors and Instrument Requirements for Autonomous Underwater Vehicles

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Abstract

Autonomous underwater vehicles (AUV) are excellent platforms for measurements in the polar regions, especially under ice shelves and under sea ice. They have relatively high platform stability and low acoustic noise and vibration compared with surface vessels. They can sample in time and space in ways not possible with moored, drifting or surface vessel platforms. They are sometimes limited, however, in range; the power available for sensors; the understanding of the platform motion and position; the operable range of speed; and capital cost and/or operational expense (depending on the vehicle and operation). Yet a wide array of *in situ* and remote (optical and acoustic), physical, biological and chemical sensors have been successfully incorporated into AUVs. This paper suggests possible ways in which the observing capabilities of AUVs could be improved. Particular technical issues with sensors implemented on AUVs are discussed. The community's sensor needs are described: reliability, vehicle-sensor interoperability, common data format and development of AUV-specific sensors, especially for chemical and biological variables. The importance of communication between AUV owners, developers, users, funding sponsors and sensor vendors is also discussed.

1. Introduction

AUVs exist primarily as platforms for sensors that are meant to accomplish specific research tasks. For a number of reasons, AUV platforms allow research tasks that are difficult, expensive or impossible any other way. The often ice-covered polar regions particularly benefit from the advanced sampling ability of the AUV. Until the advent of towed and autonomous vehicles (and satellite remote sensing platforms), oceanographic studies (of both open and ice-covered seas) were typically 'vertical' in nature. That is, the vertical structure was measured with much higher resolution than the horizontal structure.

Oceanographers appear to be in the fortunate position that the vertical dimension is not only easiest to measure, but that the resolution of horizontal sampling does not need to be high to glean useful results. Perhaps, however, the lack of sophisticated sampling has led to this perception. The navigation and sampling capabilities of the AUV continue to uncover important oceanic phenomena, such as shallow-water hydrography (Levine *et al.*, 1997); upper-ocean mixed layer processes (Thorpe *et al.*, 2003); under-ice boundary layer processes (Hayes and Morison, 2002); surface wave attenuation in sea ice (Hayes *et al.*, 2006); and herring and krill distribution and abundance (Fernandes and Brierley, 1999). Geophysicists and ice physicists also benefit from the capabilities of the AUV, which has become a useful remote sensing tool for ice thickness distribution and morphology (Banks *et al.*, 2006; Wilkinson *et al.*, 2006), seafloor mapping, photography and sub-bottom profiling, among many others.

Of course, there are several issues that limit the use of the AUV platform. The major factors are the range of the vehicle, the power available for sensors, the understanding of the platform motion and position, and the operable range of speed. Sometimes capital cost and/or operational expense make more traditional platforms preferable. Also, the flexibility and complexity possible in sampling sometimes requires advanced analysis techniques. In this paper, we will discuss in more detail the present use of AUV platforms, ways in which their experimental capability might be expanded and general suggestions for future development of sensors for AUVs. Since AUVs seem particularly suited to polar marine science, we will draw many examples from polar research, but it should be noted that few, if any, sensors are exclusively polar in nature. Rather, the configuration or particular usage of a sensor is often modified for polar use.

2. Sampling Methods

AUVs are typically programmed mission by mission to follow a prescribed course, either based on dead reckoning, inertial navigation, homing, terrain-following or some combination of all of these. In 'nested' sampling, surveys are carried out with enough range and resolution to characterise the study area and locate a specific phenomenon or feature of interest. The user interprets the results and re-programmes a mission with more specific goals. For example, when sea ice pressure ridge depths are unknown, they are established by a previous run before being approached more closely in a later run. The result of programmed courses is typically a vertical (saw tooth) or horizontal (lawnmower) transect across regions expected to be of interest. Once underway, the AUV

typically has very little, if any, communication with the operator, and a limited number of mission variations are possible, typically due to safety concerns, e.g. collision or obstacle avoidance.

The advantage of user-programmed sampling lies in its reproducibility and its straightforward techniques for analysis and comparison with other observations or numerical simulations. The main disadvantage is that the phenomenon of interest may not be captured adequately. Earth science is unique in that unlike laboratory science, there is no way to repeat an experiment that was not carried out properly. Every moment appears a new set of environmental conditions outside of the researchers' control.

Therefore, if it is critical to measure a particular aspect of the environment, and it cannot be certain if it will be measured until after the attempt, it may be desirable to move to a more sophisticated sampling method. Adaptive sampling is a method of programming an AUV to respond independently of human intervention to investigate a particular feature. For example, vehicles can actively follow mesoscale eddies, convective chimneys or plumes, or search for sources of some tracer. While more detailed information is gathered (if the sampling is successful), analysis can be more difficult to interpret or compare with other data.

3. Sensor Examples and Needs

3.1 Sensor Applications

Many types of sensors have been installed on AUVs, and here we will provide a short list of the basic ones, plus some examples of polar and specialised applications. For oceanographic purposes, the conductivity, temperature, and depth (CTD) sensor is absolutely required, and a dual system is preferable for redundancy and inter-calibration. Note that in many cases, the pressure sensor of the CTD also plays a part in the vehicle navigation. One of the first implementations of a CTD system into an AUV, the Autonomous Conductivity-Temperature Vehicle (Morison, 1989; Light and Morison, 1989), was deployed under Arctic pack ice to examine winter lead convection (Morison and McPhee, 1998). Since then, many other AUVs have been used for hydrographic sampling (e.g. Levine *et al.*, 1997; Griffiths *et al.*, 2001), and it is now a routine measurement.

Other common *in situ* measurements include dissolved oxygen, dissolved nitrates, fluorescence, optical absorption and attenuation, down-welling irradiance and water velocity. These quantities are measured with nearly identical sensors to those found on lowered instruments. More complex applications have been implemented: turbulence and optical measurements (Levine *et al.*, 1996); *in situ* dissolved manganese analyser, methane sensor, and flow cytometer (Griffiths *et al.*, 2001); surface wave measurements using pressure sensors and vehicle motion (Earle *et al.*, 2002); and inference of turbulent velocities and fluxes from vehicle motion and T-S microstructure (Hayes and Morison, 2002). A more complete list with sensor details can be found in the report of the Autonomous Lagrangian Platforms and Sensors Workshop and the accompanying papers (Rudnick and Perry, 2003) by Perry ('Optical Sensors') and Johnson ('Chemical Sensors for Autonomous and Lagrangian Platforms').

Remote observations include (among others) acoustic doppler water velocity profiles; bathymetry and sub-bottom structure (Caress, 2005); ice draft (Banks, 2005); under-ice topography with multibeam sonar (Wilkinson, 2006); ice motion in wave fields (Hayes *et al.*, 2006); density and character of acoustic scatterers such as plankton, krill, or fish (Fernandes and Brierley, 1999); bubble concentration; and still, holographic, and video photography. Some experiments have synthesised *in situ* and remote observations such as the characterisation of dissipation rates in upper ocean mixing processes using shear probes, side-scan sonar and a bubble resonator (Thorpe *et al.*, 2003).

While it is true that AUVs provide a unique and useful sampling platform, there are a number of technical issues that must be addressed to achieve high quality data. It is obligatory to examine vehicle navigation performance in order to know the AUV position and position error (McPhail, 2006). For many experiments, variation in vehicle motion is a potential source of error, while for others it is a method by which a variable of interest is examined (e.g. Autonomous Benthic Explorer's (ABE) measurement of heat flux from a hydrothermal vent*). In any case, vehicle position and attitude, its rate of change and its acceleration must be measured to the degree of accuracy required by the application. Many times a model of vehicle motion is necessary to extract the effects of vehicle motion. In the case of buoyancy-driven gliders, the difference between observed and modelled vertical vehicle velocity provides insight into vertical water velocity (Eriksen *et al.*, 2001). More quantitatively, Hayes and Morison (2002) used a Kalman filter to extract turbulent vertical water velocity from the pressure-derived depth variations of a small vehicle.

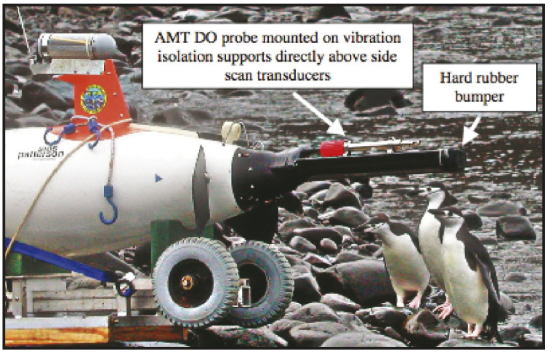
Sensor calibration and quality control may require dedicated sea trials, redundant systems, independently collected data (such as moorings) or some combination of the above. The time response of sensors must be short enough to achieve the desired resolution given the speed of the vehicle. For example, in Griffiths *et al.* (2001), the use of a methane sensor was reported, but it was noted that time response was slow relative to the dive-climb cycle of the vehicle (Autosub), and *in situ* or on-deck calibration systems were lacking.

Sensors must be robust enough to handle possible collisions with the seafloor or overlying ice. This is especially important in polar regions where bathymetric charts can be inaccurate and ice obstacles are common. For example, a fast-response dissolved oxygen probe (galvanic type) has been mounted on the Fetch1 AUV (Patterson and Sias, 1998, 1999) in such a way as to survive a collision with an uncharted pinnacle off of Livingston Island, South Shetland Islands or Antarctica. The sensor was recessed, insulated from vibrations with rubber gasket material, and a shock-absorbing pad of rubber was mounted on the vehicle's nose cone (Figure 1). Fetch1 was not untypical of small AUVs in that it did not have a forward-looking sonar; it could only avoid close approach to the seafloor (using a Raytheon 220kHz altimeter), not vertical obstacles directly in front of the vehicle.

Sensors (particularly optical) may be affected by biofouling, especially if in the photic zone, or if deployed for long periods. Copper tubing and shutters can extend useful sensor

* See http://adsabs.harvard.edu/abs/2005agufm.t31a0489t

Figure 1: Fetch1 AUV on launch/recovery dolly showing AMT dissolved oxygen sensor and hard rubber bumper on nose cone, prior to launch in the Southern Ocean off Livingston Island



lifetime (Rudnick and Perry, 2003). Research into nano-structured materials* and coatings may provide solutions in the future. Biofouling of optical surfaces, however, is not the only issue. To allow species identification during benthic surveys, it is necessary to have adequate scene illumination and colour restoration, which is difficult under conditions of low light intensity or low visibility from suspended particulate matter. Underwater video has been recorded by a Sony EVO-250 Hi8 analogue tape recorder connected to a Polaris Industries MB-1050C digital colour camera on a coral reef in Florida from a Fetch1 AUV. To achieve colour constancy and excellent colour/lightness rendition, the video was digitised and batch frame processed using a Retinex algorithm with multiscale colour restoration and lightness rendition, as implemented by Rahman *et al.* (1996; 2004). This allowed the identification of organisms and facilitated the creation of mosaics (Figure 2).

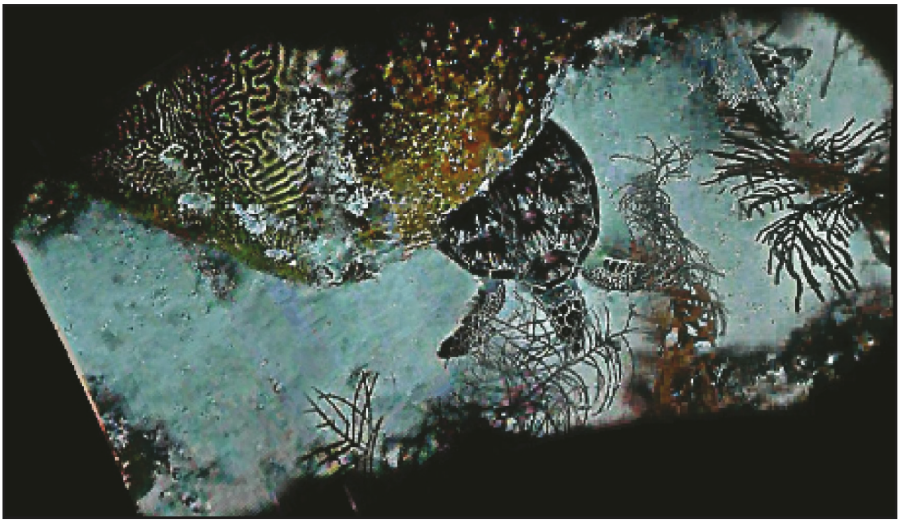


Figure 2: Mosaic from four video frames from a Fetch1 survey over a coral reef (Florida Keys National Marine Sanctuary). The AUV was terrain-following 1.5 m above the bottom at 1.25m.s^{-1}

* See http://www.ambio.bham.ac.uk/ for example

Acoustic measurements are prone to ambiguity, requiring multiple frequencies or user interpretation. For example, in measuring distance to seafloor using a Raytheon 220 kHz altimeter sonar, mounted on the nosecone of the Fetch1 AUV in the Southern Ocean, false distance to the bottom was registered if a swarm of krill (*Euphausia superba*) was present. This caused premature abort of missions where the goal was to image krill using high frequency (600 kHz) side-scan sonar and underwater video. A software override was developed to allow penetration of krill swarms and implemented on a dive-by-dive basis whenever radio-frequency telemetry from the surfaced AUV showed a false bottom. The AUV operator then entered reasonable estimates of water depth from a nautical chart, thus the AUV ignored 'too close to bottom' alarms unless the vehicle was within 50 m of chart estimated water depth. This override command thus allowed the AUV to switch into 'krill mode', which ignored the bailout state when closest approach to bottom alarm was attained.

In the case of measurement of naturally occurring sound in the ocean – from 10 Hz to 10 kHz – AUV acoustic and vibration noise may overwhelm the signal of interest. As a solution, Zimmerman *et al.* (2005) described how the propulsion system of a Bluefin AUV was modified and the eight hydrophones were remounted using a vibration isolation system.

3.2 Sensor Needs and Characteristics

The push for development of sensors for AUV use is increasing. Existing sensors are being made smaller and less power-consuming (especially for the low-power, long-range buoyancy-driven AUVs). New sensors are being developed specifically for AUV platforms. In this section a few examples and general comments for sensor needs are described.

The desire for more readily available sensors for AUVs has been identified, especially biological and chemical sensors. Many typically lab-based sensors are being developed for *in situ* use – including a flow cytometer (Tarran *et al.*, 2001; Dubelaar and Geerders, 2004); a mass spectrometer (Short *et al.*, 2001); and a Raman spectrometer* – yet power and size requirements of AUVs are now being satisfied in only a few cases. An example of a need not yet met is for microbial samplers for bacteria and viruses (sewage indicators, underwater hot vents, sub-glacial lakes, fish farms to monitor disease dispersion).

A desire for inexpensive, small, syringe system with flushing capability (seawater, sterilising and/or fixing agents) has also been identified (McGillivary, personal communication). In general, water sampling capabilities of AUVs are lacking: simple adaptations of moored samplers have proven ineffective. For a more complete discussion of the state and future directions of autonomous sensors, see the excellent report, presentations and white papers of the Autonomous and Lagrangian Platforms Workshop (Rudnick and

* See White and Tivey at
http://www.whoi.edu/dirres/funding/whoi_funding/Green/green05.html

Perry, 2003). A dedicated workshop has also taken place for *in situ* biological and chemical sensors (WHOI, 2003). While not specifically polar in nature, these workshops are directly relevant to the polar community because developing a laboratory sensor for *in situ* use is the first step towards AUV use.

As the AUV platform matures as a market for sensors, the AUV community should be in close conversation with sensor manufacturers. The unnecessary expense and effort spent by AUV users or developers in testing prototype sensors should be avoided in favour of constructive input to vendors at the design stage. Reliability is an obvious feature that should be emphasised, especially for relatively inaccessible regions like the polar ones. Due to the high capital cost of AUVs, they should have the capability to be used as a community resource. This means users should be able to plug in their favourite sensor, make minor adjustments and send the vehicle on a mission. Sensors and AUV platforms should then be interoperable in this sense. For example, Wang *et al.* (2005) suggest an electrical and mechanical infrastructure to improve the flexibility and modularity of research AUVs. While not strictly a sensor issue, it should be noted that the increasingly large and complex data streaming from AUVs need to be available in a common format for easy interpretation.

In order to provide results valuable to the scientific community with a high success rate and relatively low cost, the manner of sensor development should include a strong component of community effort. In particular, interoperability between sensors and vehicles, standard data formats and sensor reliability all benefit from feedback between the various entities involved. Sponsors, owners and sensor vendors provide financial, administrative and technical support, respectively, to developers. Engineering developers, who are usually concerned with technical solutions, are often distinct from scientific developers, who are concerned more with developing innovative scientific questions and applications for AUVs. Developers, in turn, should ideally provide tried and tested techniques and equipment to AUV users, while the latter can also be identified as research or technical operators. Between each entity, it is critical to have two-way communication, especially between research and technical types, in order for all parties to be aware of what is expected of a particular sensor and what is realistically and currently possible. The network described here should also be in communication with other networks centred around other projects in order to share common problems and solutions. A workshop environment is ideal for such exchange.

4. Conclusions

AUV platforms are suited for polar work due to their sampling capabilities and manoeuvrability. In many cases, there are no other methods of collecting the desired data in ice-covered, iceberg-containing seas. Due to the inhomogeneous surfaces, there is also unique horizontal variability in the polar oceans that can only be observed with AUVs. For new sensors, the Autonomous and Lagrangian Platforms and Sensors (ALPS) workshop (Rudnick and Perry, 2003) recommended:

Prototype sensors, particularly for chemistry, should be rapidly brought to commercialisation; development of sensors for food web studies and molecular markers should receive high priority. Miniaturisation and cross-platform compatibility must be a paramount consideration in new sensor development. Sustained investment in instrument development is essential.

Our recommendations are no different, but we would add that polar applications are especially demanding in terms of sensor reliability, longevity and robustness.

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Communications

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Abstract

This paper provides an outline of the interaction between communications and autonomy and the three major components of a communications system: the transmission pipe; the network of pipes; and the information in the pipe. Tables illustrate the subjective assessment of constraints relevant to autonomous underwater vehicle (AUV) communications in high latitudes and provide a framework for users to assess their communications requirements.

1. Introduction

Underwater acoustic communications are a limiting factor in the utilisation of AUVs. As shown diagrammatically in Figure 1, the amount of communications is directly related to the level of autonomy required onboard an autonomous system.

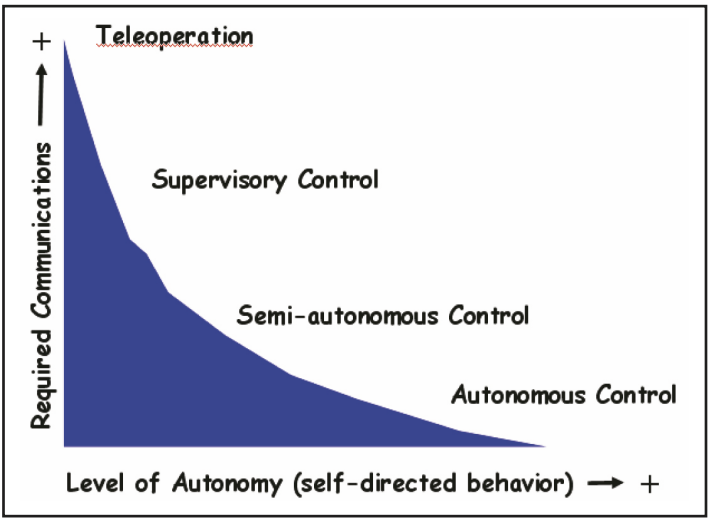

Figure 1: Autonomy versus communication bandwidth

If we are to have limited autonomy, then the communications bandwidth must be high. If we have limited communications, then the onboard autonomy must be sufficient to complete the defined task. Since a more complex task requires increased autonomy, the complexity of the task able to be accomplished must decrease as the communications bandwidth is decreased. The environment limits the effective range of communications and introduces significant noise constraints. The end result is a communication channel with very limited bandwidth. To understand this problem, it is advantageous to recognise that communications can be considered as three components: the pipe; the network of pipes; and the information in the pipe.

2. Components of Communication Systems

2.1 The Pipe

To implement communications, we must first consider the communication channel and the environment in which the channel is established; see Kilfoyle and Baggeroer (2000) for a review of underwater communication challenges and solutions. Understanding that environment and its impact on communication is the primary issue provides the constraints that must be overcome by any modem that operates in that environment. Transmission schemes, modulation techniques and receiver strategies must be implemented. Davies *et al.* (2004) present a thorough review of transmission schemes for multi-role AUV applications. In a subjective mapping of modulation modes against channel conditions and data rate, they summarise:

- Good acoustic conditions and high data rate, then single carrier modulation with quadrature phase shift keying with adaptive equalisers to reduce the inter-symbol interference from frequency selective fading has delivered 12 kbps with a bit error rate of 1 in 10^5 at a signal to noise ratio of 15 dB
- Under 'modest conditions', and in channels where multi-path leads to longer arrival time spreads, multi-carrier techniques – such as coded orthogonal frequency division multiplexing – as advocated by Bessios (1996) are well suited. In their simulation, Davies *et al.* (2004) predicted that such a system, using Viterbi coding, would achieve a data rate of 3 kbps at a bit error rate of 1 in 10^6 at signal to noise ratios of over 5 dB
- With very poor acoustic conditions, frequency hopping and direct sequence spread spectrum techniques give robust communication (bit error rates of 1 in 10^6) down to signal to noise ratios of –15 dB, by sacrificing data rate. In Davies *et al.* (2004) the typical data rate under such conditions is 230bps.

Many of the issues for high latitude communications and navigation related to AUVs were examined at a workshop in Seattle in April 2006[1]; the interested reader is referred to the presentations for further detail.

For energy-limited AUV applications, a key performance parameter for any communication system is the energy cost of transmission, in $mJ.bit^{-1}$. Partan *et al.* (2006) discuss

[1] See http://anchor.apl.washington.edu/index.html

the energy issues. For reception, their example is ~0.4 mJ.bit^{-1} for equalising and decoding a phase shift keyed transmission (5000 bps, 2 W processing power consumption). Two examples, from the LinkQuest range of wideband underwater modems[2], give an indication of what is currently achievable in transmit mode:

- Short-range, shallow water (UWM1000): 0.3 mJ.bit^{-1} – over an omni-directional range of 350 m at 7000 bps usable throughput and a bit error rate of less than 1 in 10^9 with 2 W
- Long-range (UWM10000): 20 mJ.bit^{-1} – over an omni-directional range of 7 km at 2000 bps usable throughput and a bit error rate of less than 1 in 10^7 with 40 W.

Radio frequency (RF) communications simplify establishment of a communication channel, but introduce other issues that must be considered. The Iridium satellite system covers the polar regions and provides short burst (mobile-originated messages of up to 205 bytes, mobile-terminated messages of up to 135 bytes with a low latency of less than one minute), dial-up data at up to 2.4 kbps and direct internet connections through Iridium servers[3]. As a specific example, an Iridium system has been used with two-way communication from a polar sea ice thickness–measuring platform[4]. In terms of energy per bit in dial-up mode, it is about twice that of short-range acoustics at ~0.6 mJ.bit^{-1} (2400 bps at 1.5 W). Terrestrial radio telemetry is more frugal; the Freewave GRO9CSU 900MHz modem operating at 115 200 bps consumes a maximum of 6 W for a range of up to 60 miles, an energy cost of ~52 μJ.bit^{-1}.

2.2 The Network of Pipes

More importantly, multiple agent systems require the ability to communicate over a network environment where any vehicle can talk to any other vehicle directly, with a command centre or to all of the vehicles in the group using a broadcast mode (Sozer *et al.*, 2000; Akyildiz *et al.*, 2005). This requires a network protocol that functions efficiently in the underwater environment with its noisy communication channel with limited bandwidth (Heidemann *et al.*, 2006; Partan *et al.*, 2006). To provide a network environment where mobile and non-mobile nodes can communicate over an underwater network with reasonable bandwidth and high reliability is a lofty goal (Proakis *et al.*, 2001).

In an informative paper, Partan *et al.* (2006) set out their taxonomy of underwater networking as a two-dimensional space with axes of 'area covered by nodes' and 'node population'. They consider that medium access protocols (MAC) remain unresolved for the underwater domain even though MAC for RF communications has been well understood for decades. Particular issues underwater include: sparse networks; contention between acoustic navigation and acoustic data reception/transmission and network motion (including the significant issue of the doppler effect); and the communication channel issues.

[2] See http://www.link-quest.com/html/uwm_lr.pdf
[3] See http://www.iridium.com/service/iri_service-detail.asp?serviceid=2
[4] See http://iridium.mediaroom.com/index.php?s=press_releases&item=772

2.3 The Information in the Pipe

Clearly whatever bandwidth is available in an underwater or terrestrial communications channel, the amount of information needed to be moved through that channel will exceed its capacity. Methods must be developed to abstract information and data to optimise the number of bits to be transmitted across a communication channel.

3. Current Communication Systems Capability

If we consider available communication systems, it is possible to make some subjective understanding of the constraints involved that will impact the utilisation of AUVs. In many areas there will be increases in capability over the next few years. In others there are physical limits to what can and cannot be done. Table 1 attempts to summarise some of those issues.

Although the discussions at Masterclass in AUV Technology for Polar Science did not specifically focus on the needs for communication in any depth, it was clearly under-

Table 1: Characteristics of various communication systems

	RF (e.g. Freewave)	**Satellite (e.g. Iridium)**	**Acoustic**
Pipe	Reasonable data rates Cost minimal issue Mechanical integration	Costly Limited access Low data rates Coverage in polar regions	Limited range High latency Limited data rates Noisy, unreliable channels Channel access not guaranteed
Network	Networked systems? RF/acoustic interface Limited range Antenna issues	Latency Integration with other protocols	No standard protocol Overhead impacts data rate Interface
Information	Few information standards Limited bandwidth No accepted languages	Few information standards Limited bandwidth No accepted languages	Few information standards Limited bandwidth No accepted languages

Table 2: Communication requirements for AUVs

	Status	**Commands**	**Emergencies**	**Data / Info**
Access	Scheduled	Scheduled	Unscheduled	Scheduled
Bandwidth	Medium	Medium	Low	High
Reliability	Medium	High	Very high	Low
Quality	Medium	High	Very high	Low to very low
Latency	Minimal	Minimal	Minimal	Low
Cost	Low	Minimal	Not important	Minimal

stood that the technology was an important part of future systems working in extreme environments such as the polar regions. There was also some agreement that communication requirements could be broken down into a few categories with different requirements associated with those categories. Table 2 is an attempt to diagram a draft of those categories with some qualitative definition of the requirements associated with those categories.

Qualitative assessments of the required communication capabilities remain as only a starting point for defining the real needs associated with some of the missions considered for AUVs. It was hoped that more quantitative information could be obtained during the Masterclass meeting. Although this did not happen, some insight was gleaned from the participants at the meeting. Table 3 diagrams some of the thoughts that resulted at the meeting. It remains an exercise for the reader to fill in the missing numbers to help define the future needs.

Table 3: Communication channel characteristics

	Status	Commands	Emergencies	Data / Info
Access	1 per 4 hr			
Bandwidth	200 bps			
Reliability	8 of 10			
Quality	1 in 10^5			
Latency	Minutes			
Cost	£0.50 per block			

In summary, although all at the meeting recognised communications as an important, possibly troubling, technology requirement for future missions using AUVs, many other issues also loom in front of near-term deployment of autonomous data gathering vehicle systems. Time did not allow for in-depth consideration of the communication needs and/or possible solutions.

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Future Technologies and Requirements

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Abstract
There is increasing interest from the marine science community in using autonomous underwater vehicles (AUV). However, experiences from science missions with existing AUVs show poor reliability, although the scientific value of the information collected from these vehicles are considered high. The paper discusses reasons for this and suggests that manufacturers of AUVs should adopt best practices from other industries with similar requirements for reliability and technology content. The paper also discusses how future requirements in ocean and polar science may require AUV technology developments in specific areas.

1. Introduction

AUV technology is in its infancy. The story has just begun. Today AUVs can do simple tasks under benign conditions over a limited amount of time. Even with today's limited technical performance, though, they are still able to bring significant value to user organisations in specific areas. As the technology evolves, the value that AUVs generate for the users, and the number of applications where this technology are cost effective will increase. This paper discusses how technology developments may impact the use of AUVs in ocean and polar sciences.

The recipe for quick market access of AUVs is not just a matter of technological excellence, though. There is a long list of potential problems that have delayed the acceptance of AUVs by user organisations. To mention only a few:

- **Reliability** – they break down too often, and with possible fatal consequences (fatal for the vehicle, that is)
- **Legal issues** – unclear legal maritime status of AUVs and liability consequences
- **Organisational issues** – they do not fit into existing operational concepts or logistics
- **Financial issues** – initial investment is high, even though they are cost effective to use
- **Mental barriers** – using underwater robots may be too far fetched for most people in conservative businesses.

However, for applications where *force multiplying* effects are acknowledged; *and* where AUVs may be introduced without major changes in existing operational infrastructure and concepts; *and* where money is not the limiting factor, the threshold for use may be low enough to overcome the scepticism in user organisations. The offshore oil and gas industry and the defence fit all these requirements, and these two sectors have 'volunteered' to take the initial risk of pioneering AUVs.

The first application for AUVs in the oil and gas industry has been for offshore seabed surveys. The driver for this industry to take on AUVs has been the general trend towards using subsea production facilities and exploitation of oil and gas in very deep waters. The developments of such production facilities are complex and require very high quality seabed documentation as a prerequisite for the field design process, and for the planning and execution of site and pipeline construction and verification. This documentation includes high-resolution, high-precision topographical seabed maps, high-resolution acoustic imagery, sub-bottom characterisation and oceanographic information. Going deep adds to both the complexity and the risk associated with the development of these subsea production facilities, thus increasing the need for high-quality site documentation. At the same time deep waters increase the challenge of maintaining sufficient data quality (mainly related to the accuracy of geographic positioning) and these survey operations tend to be cost intensive.

AUV technology has shown to bring a cost-effective solution to this business (Størkersen *et al.*, 1996) and a sustainable international industry has developed in this area over the

last six to seven years. The pioneering development was done during 1995–98 in Norway by a consortium of Statoil, Kongsberg Maritime and Norwegian Defence Research Establishment (FFI), together with the survey industry. The delivery from this development was two prototype systems (HUGIN I and II). The HUGIN technology was later commercialised by Kongsberg Maritime and vehicles are now operated by various survey companies worldwide (Vestgård *et al.*, 2002; Northcut, 2004; Kleiner, 2004).

To date (2006) some 100 000 km (equivalent to 2.5 times around the earth) and more than 10 000 operational hours have been accumulated by the survey industry with these systems (Hagen *et al.*, 2006). This means that the offshore survey industry owns by far the most extensive knowledge base on operational experience of AUVs. There have been survey contracts awarded in areas in five continents – ranging from Arctic to tropic conditions – at water depths down to 2900 m. They have been operating in harsh environments, rough underwater seabed terrains and heavy sea states on an around-the-clock basis, and have developed a commercial streamlined data production for seabed information with a high degree of quality assurance associated to it.

Also the military segment is now in the process of introducing AUVs into its naval defence structure. The US Navy has been the lead entity in this process, both through firm visions of military use of AUVs (US Navy Masterplan, 2004) and aggressive technology developments funded by the Office of Naval Research (ONR) and Naval Sea Systems Command (NAVSEA). In Europe nations have started processes to transform technology into capability. Both Finland and Norway (Hagen *et al.*, 2004) have ongoing acquisition programmes for AUVs that will enter into regular military operation, and other nations have acquired AUV prototypes for operational evaluation purposes.

The ocean science community also has a great potential to benefit from AUVs, however, lack of appropriate national funding mechanisms (except for the UK) have up to now precluded extensive use of this technology. The pioneering work with AUVs in ocean and polar sciences was done some 20 years ago by International Submarine Engineering (ISE) and Defence Research and Development Canada (DRDC), which developed and demonstrated specialised AUVs (ARCS and *Theseus*) for under-ice exploration in polar regions (Ferguson, this volume).

During the 1990s Southampton Oceanography Centre* in UK developed the Autosub system which has been used extensively both in the Arctic and the Antarctic regions (McPhail, this volume). In the US, Woods Hole Oceanographic Institution (WHOI) and Monterey Bay Aquarium Research Institute (MBARI) also have performed challenging science missions with AUVs in both deep waters and under arctic conditions (refer to other chapters in the book). In Norway, the Institute of Marine Research (IMR) has performed a number of scientific missions for fish stock measurements and for coral reef characterisation (Vestgård *et al.*, 2003), and in Japan several prototype AUVs have been developed for scientific purposes, such as the *Urashima* AUV (Yamamoto, this

* Now the National Oceanography Centre, Southampton

volume). However, scientific use of AUVs is still in an early stage of evolution and technology is not quite mature enough for the most demanding mission categories, thus focused developments need to be encouraged in order to provide robust AUV services to this community.

2. General Requirements for Future Ocean Science Surveys

AUVs are effective tools for scientific data acquisition: they are very benign as multi-sensor platforms and thus provide very high-quality data; they can be used to investigate and track specific features and processes; and they can visit ocean areas not easily accessed by other means (e.g. very deep waters and under ice). They may be operated under control from a research vessel using acoustic communication to provide real-time feedback to the scientists of the features to be investigated. They may also be operated all the way to full autonomy, where the AUV is sent on its own from a shore station or from the research vessel, thus increasing scientific productivity or reducing the overall cost of scientific data acquisition.

In general terms the technical requirements for ocean science applications capture both the offshore and the military requirements, as these sectors need robust and reliable systems with long endurances for very deep waters in harsh environments (in line with the offshore requirements), and sophisticated control autonomy (from military requirements) to enable surveys without surface support and under ice.

Generally speaking, we want AUVs to be able to do more and to perform better than they do today. We want them to

- Go longer
- Go deeper
- Go under ice
- Go on its own
- Make it back home
- Cover more ground
- Improve data quality
- Work in bad weather
- Adapt to the environment
- Adapt to sensor information
- Be able to probe the environment
- Carry more sensors simultaneously
- Interact with other autonomous systems
- Report back to base and re-task mission from base.

If we map these general requirements to technology components, we get the matrix in Table 1.

Table 1: Generic requirements versus technology consequences

Mission Requirements	Consequence for Technology
Go longer	High energy density power sources
Go deeper	Mechanical design, structural issues, navagation & control
Go under ice	Autonomous control, communication, sustainability
Go on its own	Autonomous control, adaptive behaviour, sustainability, recovery
Make it back home	Sustainability, autonomous control, lauch and recovery
Cover more ground	Power sources, sensor performance
Improve data quality	Sensors, navigation
Work in bad weather	Launch and recovery, sustainability, mechanical issues
Adapt to the environment	Autonomous control, adaptive behaviour, real-time sensor processing
Adapt to sensor information	Autonomous control, adaptive behaviour, real-time sensor processing
Be able to probe the environment	Intervention capability, vehicle design
Carry more sensors simultaneously	Sensors, sensor processing
Interact with other autonomous systems	Autonomous control, communication
Report back to base and re-task mission from base	Autonomous control, communication

The technology areas that will impact future ocean science missions may be categorised as follows:

- Control technology (control autonomy)
- Navigation (navigation autonomy)
- Power sources (energy autonomy)
- Communication
- Sensor technologies (not discussed in this chapter)
- Networking of systems (system of systems)

In the following sections, we briefly discuss each of these technology areas and the need for future developments in line with ocean science requirements.

3. Future Technology Developments

3.1 Control Technology

Control technology comprises all aspects of controlling the vehicle, to make sure that the AUV fulfils its mission objectives. This area probably is the least mature of all the

technology areas in AUVs today. One crucial aspect of control technology is to establish the ability to sustain operation, even when critical components fail. This prerequisite is necessary to obtain overall reliability over the extended periods of time required in future missions (weeks) and when operating under ice. The ability to provide a graceful degradation of mission parameters if internal failures occur, and still bring home the essential scientific information (or at least the vehicle itself), will be a crucial property of AUVs of the future.

The term 'sustainability' captures a range of features, all linked to the overall ability to enable an AUV to sustain operation. One of these features is system integrity control (internal situation awareness). Another is the actual repair strategy (which is a control system in itself) when integrity control has detected error situations. Alternative use of subsystems requires a certain level of 'redundancy' in the AUV. In order to find the right balance between redundancy, reliability and complexity, best practise systems architecting/engineering methods must be used.

The use of other standard industry methods for operational risk reduction, such as hazard and operability studies (HAZOP), has shown to be valuable in the design phase of AUVs. Of course the reliability of subsystems, such as mechanical and electrical components, must also be improved in the future, as current experience with AUVs is that 'it is not the high-tech that fails, it's the low tech'. However, the use of industry standards for component quality verifications and best practices of systems design and engineering (e.g. from the car, aviation or space industry) will potentially reduce failure rates dramatically from today's figures.

Another aspect of reliability is human factors. Experience shows that most aborted AUV missions are caused by human error. More sophisticated automated built-in-test systems, mission simulation software and extensive hardware-in-the-loop testing; along with elaborate manual pre-launch control procedures, will be mandatory in future AUV operations.

The other part of control technology relates to handling of the external processes. Adaptive mission management that is goal driven, rather than executing sequenced manoeuvres, will emerge in future AUVs. These systems will be able to continuously re-plan during mission using the accumulated knowledge about the mission, in order to optimise final mission outcome. They may extract information from sensor data to avoid obstacles, find a better route through an area, autonomously revisit target objects that need to be further investigated or track features or gradients in the water column or on the seafloor. Adaptive behaviours involves a series of techniques, from low level sensor processing and fusion, to automated target recognition (ATR) and local decision support, to high level mission management and goal management.

AUVs may also be operated in controlled mode, i.e. controlled from a surface ship with acoustic communications links. The added benefit of this, in addition to the man-in-the-loop for operational control, is that scientists have real-time data from the AUV and

may work adaptively with the AUV as they investigate information, e.g. by re-routing the vehicle to revisit areas of interest without recovering the AUV, or optimising sensor performance, by adjusting parameters and observing the effect on the fly.

3.2 Navigation

Navigation of AUVs serves two purposes; one is to be able to run the AUV through the predefined route with sufficient accuracy (i.e. to place the sensor in the correct position), and the other is to be able to geographically position the sensor data (i.e. the actual features to be investigated) within the accuracy required. The requirement for accuracy will depend on the type of data and the use – e.g. detailed seabed bathymetry for offshore applications needs a very high global positioning accuracy (typically one metre, standard deviation), whereas oceanographic data may suffice with hundreds of metres. The value of the information itself is often linked to these quality parameters and to the ability to document actual quality. To investigate features on the seafloor (which changes over time) by revisiting the same area on a regular basis requires good positioning accuracy to be able to correlate one data set to the other, e.g. when documenting the wear of coral reefs due to commercial fishing or environmental impact.

AUVs for high-value missions are equipped with an aided inertial navigation systems, which include a variety of sensors with fairly advanced navigation processing. The inertial navigation system (INS) calculates position, velocity and attitude of the vehicle using high frequency data from an inertial measurement unit (IMU). Without other sensors to either limit or bind the error of the INS, it will drift off at a rate of typically 2 km per hour. Aided by a doppler velocity log (DVL) with bottom-track and a depth sensor, the drift will typically be reduced to a few metres per hours on straight line trajectories (Jalving *et al.*, 2003).

For long missions or ones that require very high data accuracy, more aiding sensors and aiding techniques are required. If possible, surfacing for global positioning system (GPS) fix will be the natural choice, yet this is impractical when operating in deep waters or under ice. When operating in conjunction with a research vessel in open waters, the solution will be to send down GPS ultra-short base line (USBL) position updates to the AUV over acoustic communication, thus binding the drift of the local INS. When operating under ice, the use of long base line (LBL) or underwater transponder positioning (UTP) (Jalving *et al.*, 2003) or other related techniques with deployment of transponder beacons through the ice are possible (though not always practical) options to secure accuracy over extended periods of time.

If a high-resolution topographical map (digital terrain model, or DTM) of the area is available, the AUV may be able to avoid error drift by using a multibeam echosounder (MBE) or a DVL to measure terrain profiles and correlate with the DTM. Special features on the seabed that are *a priori* known to the AUV may also be used to bind the navigation error. All of these aiding techniques have been demonstrated in AUVs and will be used in them in the future. Further techniques under development include con-

current mapping and navigation (CMN), where the AUV may be able to further exploit terrain, or feature-based navigation in unknown areas by repeatedly visiting known areas for updating and refining of the reference database of the unknown area.

3.3 Power Sources

High energy density power sources need to be developed further to enable us to exploit the true operational benefits of AUVs. Ideally, we want AUVs to be able to operate continuously over many days (weeks even) with a powerful multifunction sensor suite on board. One solution to achieve longer endurance is to make the AUVs bigger, since endurance scales with volume, yet at the same time we would like to limit the overall size of the vehicle body to enable simple operation from vessels of opportunity. Obviously with the current state of batteries and fuel cells, this means introducing compromises. Improvements in battery and fuel cell technology is therefore one of the areas that will provide most benefit to the applicability of AUVs.

When comparing various alternative power sources for AUVs, the intimate relation between the power source and the vehicle itself must be taken into consideration. This means that the quality figures normally stated by the battery manufacturers, e.g. energy density, do not apply directly unless a specified set of assumptions are made. For instance, we must take into consideration that the weight of the vehicle must be equal to the Archimedes buoyancy force for the vehicle to be neutrally buoyant. To compare alternative power sources on equal terms, we must therefore assume that the power source itself is neutrally buoyant. Thus, in addition to the plain power source, weight and volume for buoyancy material and pressure containers must be added to calculate the true energy density in the AUV.

In this buoyancy calculation, the operational depth then comes in as a driving parameter, due to both the specific density of available buoyancy material increasing with depth rating and the weight of pressure containers increasing with design depth. Therefore, both operational (maximum) depth and the specific materials used for buoyancy and containers (aluminium, titanium, fibre-reinforced plastic or glass containers) should be specified to compare properly the electrochemical power sources for AUVs.

Some electrochemical power sources (e.g. fuel cells) are highly complex and hence need advanced auxiliary systems and fuel storage units to operate. These auxiliary and fuel storage systems do not necessarily scale linearly with energy production. Therefore, there will be minimum vehicle size (i.e. battery volume) that can accommodate these technologies, and the energy density of these technologies will be dependent on actual volume.

When ranging power sources with increasing AUV endurance, assumption must be made about the size of the vehicle itself, the fraction of the total volume allocated to batteries and the power cycle pattern. Vehicle size itself is an important parameter, since the available energy onboard scales with volume, whereas propulsion power in general scales with surface area. This means that endurance requirements are easier to meet in large vehicles than in smaller ones. The power load consists of propulsion and hotel load (sensors and other systems except the propulsion motor, or motors). Propulsion power

is highly sensitive to vehicle speed (in third power), which means that the penalty of designing AUVs with nominal speed beyond the 3–4 knot window is usually too high.

Electrochemical power sources for AUVs may be divided into four different groups (1) standard batteries inside a pressure container and working at normal pressure; (2) pressure compensated batteries working at ambient pressure, but electrically insulated from the seawater; (3) seawater batteries; and (4) fuel cells.

Examples in the first category are conventional lead- or nickel-based rechargeable batteries, silver-zinc rechargeable batteries and primary and rechargeable lithium batteries. In the second category, examples are lithium-polymer ambient pressure batteries and aluminium-hydrogen peroxide batteries (semi fuel cells). Seawater batteries make use of the environment (the sea) itself in the process of generating energy, and therefore fall into a category of its own. Fuel cells are a family of technologies operating on hydrogen fuel and oxygen.

When comparing power sources, a number of factors should be considered in addition to specific energy (and power) capability, typical factors being cost, battery life (both in terms of cycle and calendar life), maintenance requirements and safety. In Table 2 the technologies that have been used in AUVs to date (or in progress of development in conjunction with a specific AUV program) are listed.

Table 2: Typical performance figures of electrochemical power sources in a generic AUV of a total volume of 1.2 m³

Technology	Type	Energy Density (Wh/dm³)	Endurance (hours)	Safety	Cost	Logistics/ Maintenance
Lead acid	Rechargeable	10–20	4–8	High	Low	Low
NiCd/NiMH	Rechargeable	10–30	4–12	High	Low	Low
Alkaline batteries (heated to +45 deg C)	Primary	10–30	4–12	High	Low/ high	Low
Silver-Zinc	Rechargeable	30–50	12–20	Medium	High	Medium
Lithium ion (D-cells)	Rechargeable	40–70	16–28	Medium	Medium	Low
Lithium polymer (pouch)	Rechargeable	50–75	23–30	Medium	Medium	Low
Aluminium-oxygen	Semi fuel cell	80–90	32–36	Medium	Medium	High
Hydrogen-oxygen	Fuel cell	100+	40+	Low	Medium	High
Lithium batteries	Primary	100–150	40–60	Low	High	Low

The following assumptions have been made in the performance calculations: AUV volume is 1.2 m^3, with 25 percent of the total volume allocated to the power source. It is assumed that this volume is kept neutrally buoyant by using syntactic foam with a density of 550 kg/m^3 and aluminium (Al 6082 T6) as the pressure container material. Maximum design depth used in the calculations is 1000 and 3000 m. For the endurance calculations, a propulsion power of 350 W (corresponding to constant velocity of approximately 4 knots) and a hotel load of 400 W have been used.

In the low performance end, we find the conventional lead-acid and nickel-based rechargeable technologies – which are simple, benign and low-cost systems – are often used in AUVs for testing and experimentation. Alkaline primary batteries are also benign batteries to use, but are slightly more temperature sensitive. Operational cost mayo be high if the AUV is to be used on a continuous basis, as the cost is more or less proportional to operation time. The silver-zinc technology was mostly used in the early period of AUV history, but due to high initial cost and low cycle and calendar life, this system is no longer the preferred choice for modern AUVs.

A great leap in performance came with the introduction of rechargeable lithium ion (Li-Ion) batteries, which may sustain vehicle operation for about one day for small and medium sized AUVs. They are simple to use and have good cycle life, thereby providing acceptable overall lifecycle cost. Safety is acceptable, if the proper best practices in battery design and operation are employed.

A derivate of the Li-Ion technology, which has just recently been commercialised, is the lithium polymer batteries. These power sources may be operated at ambient pressure, using polymer poach cell technology from the electronics industry (PCs, mobile phones, etc). These poach cells are stacked into cell modules and moulded in a polymer resin, which are then stacked into larger battery modules. Performance is similar to the conventional Li-Ion batteries, but they are insensitive to operational water depth, which make them especially attractive for deepwater AUVs.

Semi-fuel cells based on aluminium metal anodes, hydrogen peroxide (oxygen) and alkaline electrolytes have been used by the commercial offshore industry in the HUGIN 3000 AUVs since 1998 (Hasvold *et al.*, 2002). These systems operate at ambient pressure and are therefore very attractive in deepwater systems (e.g. 3000 m). Recharging is done by replacing consumed anodes and electrolytes between dives. Turnaround time is low (less than four hours) and endurance is high (60 hours in HUGIN 3000, which is a larger vehicle than the one used in the calculations above). The system is fairly complex and involves onboard infrastructure and logistics that requires skilled personnel for operation.

Hydrogen-oxygen fuel cells are now approaching maturity in other applications (e.g. air independent propulsion for conventional submarines), but are only in its infancy when it comes to AUVs. Fuel cells have a fair potential in the future, in particular in the larger AUVs. Primary lithium batteries provide very high energy density and endurance, but

cost and battery safety is of great concern. This will limit the use of primary lithium batteries to applications that are valued important enough to accept the very high risk and cost levels.

Seawater batteries, in particular batteries that exploit the oxygen in the ocean, have also been used in AUVs (Hasvold, 1993; Hasvold *et al.*, 2004). However, these systems have not been included in Table 2, for the reason that the design of the battery is so tightly integrated with the vehicle itself that it is not possible to comply directly with the initial assumptions. The general performance attributes of seawater batteries are a very long endurance capability, but a low power (load) capability that limits the application to a low power sensor suite.

The seawater battery concept is based on the use of seawater as electrolyte and dissolved oxygen in the ocean as the oxidant in a semi-fuel cell with magnesium anodes as fuel. The advantage of this concept is the increased ratio of energy to weight and volume compared to traditional battery technology. During operation, a flow of seawater through the battery supplies the electrodes with oxygen and removes the products of the reactions taking place in the battery. Two prototype vehicles (AUV-demo and CLIPPER) with seawater batteries have been built (Hasvold, 1993; Hasvold *et al.*, 2004). The design endurance capability of the CLIPPER vehicle is of the order of 1600 nautical miles over two to three weeks. This corresponds to the distance between the Svalbard islands and Alaska crossing the North Pole. However, only low power sensors may be operated from the seawater battery, and we still need developments on other areas of AUV technology to sustain such long missions.

3.4 Communications

The ability for AUVs to communicate underway serves at least three purposes (see also Blidberg, this volume). The first is to communicate sensor data in near real time so that scientists may respond immediately to the information within this data and adjust sensor or mission parameters adaptively to optimise overall results. Such real-time interaction often proves to be effective when new equipment (e.g. sensors) is being tested, or when unpredictable scientific features are being investigated. The second is for quality control of data and of the AUV itself, so that the mission may be safely aborted if something goes wrong. Also communicating own position and status when dead in the water or on the surface is a crucial feature in any AUV. Finally, the ability to communicate with other AUVs or stationary equipment on the seabed will give possibilities for new scientific applications and configurations involving AUVs.

Although long-range underwater communication is subject to extensive research worldwide, such communication systems will, in foreseeable future, still have limited range and low bandwidth and remain unreliable. What we may hope for is typical performance of a few bits per second over hundred kilometres, a few hundred bits per seconds over tens of kilometres and a few tens of kilobits per second over a few kilometres. Some times there will be occasional drop-outs caused by changing environmental conditions

that will destroy the acoustic channel between transmitter and receiver altogether. This is something that we will have to live with. Low data rate and unreliable performance lead us to an operational philosophy that gives priority to control autonomy rather than to man-in-the-loop. Maintaining man-in-the-loop will add to control and safety, but may not be expected at all times. To emphasise development of intelligent and effective compression techniques and transmit high-level information rather than raw data are obvious approaches to alleviate the limitations.

For ocean science applications most data are not time critical and may await physical recovery of the AUV after mission. More important is to get across vehicle status parameters, or 'heart beats' even, that may be transmitted with only a few data bits. Research emphasis for this community should therefore be on extreme long-range and robust communication techniques, in particular for use under ice.

Satellite communication to complement regular radio communication when on surface will be a mandatory requirement for most ocean-going AUVs. Global connectivity provides the opportunity to interact remotely with the AUV, even from one's home office. To use company experts to do remote diagnostics to fix problems may save a lot of time and money. For polar science applications Iridium seem today to be the preferred choice because of satellite coverage in the polar regions.

3.5 Networking of Systems

The mechanisms that are being investigated by the ocean science and marine research communities are extremely complex by nature. Future research activities will therefore need to be more co-ordinated and will involve a much wider range of assets, and the results will be put into much broader contexts than before. Curiosity-driven single experiments focusing on local observations (key-hole research) do not provide the true picture for which this community is looking. We will rather see multidisciplinary teams of experts who will bring to the table a broad spectrum of observation systems, instrumentation and modelling techniques that are able to establish a seamless link between global and local, short-term and long-term effects. Assets like sophisticated satellites, massive arrays of moorings and floats, 'fleets' of research vessels with instrumentation, sampling equipment, remotely operated and autonomous underwater vehicles and gliders will work together to input ocean and environmental modelling, climate forecasting and fisheries management activities. One example of such an initiative is the Autonomous Ocean Sampling Network (AOSN) funded by the ONR (Bellingham *et al.*, 2002).

AUVs bring new possibilities to such observation and sampling networks or other forms of co-ordinated operations, and new requirements may rise from their use in this context. Options will be to deploy AUVs permanently on remote underwater observation sites to supplement data acquisition from stationary equipment, to do coordinated operations with other AUVs or gliders, and to shuttle information from under ice or to link stationary observation nodes by doing measurements between the nodes. Most

of these new modes of operation are facilitated by technology advancements already discussed. However, the added complexity of co-ordinated operations, and the requirements for specific architectures and infrastructures to accommodate such operations, make it a problem area of its own. It will be beneficial to take advantage of military developments, since network based operation is one of the strong drivers for facilitating the military use of AUVs.

4. Conclusions

AUVs for ocean and polar science applications will still need significant developments before they may be acknowledged as mature and reliable. However, this is not primarily because of technology deficiencies, as technology is available today for performing many valuable scientific missions. It is more a matter of employing best practices in systems design and engineering – using known principles from other industry segments such as the car, aviation and space industries. The ocean science community may also benefit from experiences from the oil and gas industry, which has already used AUVs on a commercial basis for many years, and from the military sector, where operational requirements pose severe challenges to technology. To realise the full potential of AUVs in marine research, advances in autonomy, power sources, communication and network technologies are needed.

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Autonomous Underwater Vehicle Operations – Needs of New Users

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Abstract
To date most autonomous underwater vehicle (AUV) operators have been heavily involved in the development of the vehicles, but as the technology matures, more users are becoming involved in operations and these operators see the AUVs primarily as tools for industry/commercial and science missions. This chapter addresses the needs of new users making decisions on whether and how to operate AUV(s) within their organisation. The aspects considered include: personnel, funding and insurance and safety. Personnel issues include recruitment, skills and education, and training and management. Funding is required for capital, operating, maintenance and repairs, and upgrades and replacement. Insurance is a large cost item and is affected by the very small numbers of users. Safety issues include safety of the vehicle itself and safety of others due to operations of the vehicle: loss and recovery, damage during launch, collisions, operating protocols, regulations and legal issues, and operating personnel and support vessels.

1. Why Use an Autonomous Underwater Vehicle

AUVs provide a means to do a wide array of research in the oceans and in hazardous underwater environments. Their advantages include:

- Versatility to deploy a wide range of sensor payloads
- Ability to send the vehicle to remote locations that cannot be accessed with a tether or link to the surface, such as under sea ice, ice shelves, land-fast glacial ice and deep ocean locations
- Ability to execute extensive surveys autonomously and without the constant support from a surface vessel, often with a relatively small vehicle
- Missions that involve measurements taken in the oceans at accurate predetermined times and spatial locations in the three-dimensional space of the water column, leading to sampling strategies, are not possible with conventional oceanographic instruments.

However, AUV operations are still relatively novel and it is not widely known how to operate these vehicles safely and reliably. Some guidance is available in the form of *The Operation of Autonomous Underwater Vehicles, Volume 1: Recommended Code of Practice* written by members of the Society for Underwater Technology's Underwater Robotics Group (Dering, 2000). Also, Griffiths, Millard and Rogers (2003) reviewed the major issues of risks, procedures and logistics with AUVs. New users face many common issues that have already been addressed by experienced users, and this paper discusses some of these issues from the perspective of the potential new operator. Several of these issues are also relevant to an experienced AUV operator entering a new technology, e.g. a user of propeller-driven AUVs becoming a user of underwater gliders or vice versa.

2. Personnel

Skilled personnel are key to successful AUV operations and yet there are no schools for AUV training. The questions regarding personnel that arise for a new operator are concerned with:

- Who, how many and where to recruit?
- Skills and education needed:
  - organisational
  - operational
  - technical (hardware/software; mechanical/electrical)
  - safety/recovery
- Training with minimum risk to staff and equipment
- Management structure
- Salary, benefits, additional payments suitable for operations staff
- Willingness and ability to work at sea and in hazardous environments.

Training is paramount and must, at a minimum, include sea acceptance trials, initial operator training and mission design with the manufacturer of the vehicle (Figure 1). Manufacturers of vehicles have a wealth of information and expertise on their vehicles which can be used to advantage by a new team. Further experience can be gained by seconding personnel to experienced teams that already operate vehicles to learn how the vehicles are operated in different conditions – such as launches in realistic ocean conditions and how certain sensors can be integrated with the vehicle operating systems.

Figure 1: International Submarine Engineering Ltd personnel and the Memorial University new user team undergoing sea acceptance trials and training with the MUN Explorer AUV

The operating team needs leadership that will consist of an overall visionary leader of the group operating the vehicle, as well as a hands-on operations leader or manager who is in charge of, and takes responsibility for, each and every operation and mission. The visionary leader will need to be involved in fundraising and raising the profile of the vehicle and its projects. The operating team must be built on teamwork with multi-skilled and versatile personnel who work well as a group. A team needs mechanical, electrical, electronic and software skills to operate the equipment, in addition to capable handling personnel to deploy and recover the vehicle (e.g. Figure 2). Certain situations, such as multi-day operations onboard ships or at ice camps in polar regions, will involve round-the-clock use and the team must be structured to meet these challenges.

Figure 2: Calm water launch with conventional slings

Many AUV operations grow out of research organisations, such as universities and research laboratories. While it is important that the operating team understands researchers' needs and can communicate with them, it is also important to generate a distinctive operations mentality in the team to ensure that operating protocol is followed meticulously. For example, it would waste time in recovery and remedial work to discover after the vehicle

dives that no one checked whether the emergency beacons were switched on, or that a mission plan was generated that had not been checked by multiple personnel for errors prior to implementation.

Researchers have a tendency to want to try new approaches, but during regular operations the tendency should be resisted unless there are extremely strong reasons for moving in a new direction. A close working relationship between scientists and engineers at every stage of development and operation improves communication and keeps expectations and reality on par. Much has been said and proposed about adaptive control for AUVs, but some experienced AUV operators worry that missions that include adaptive control might involve too many unknowns as to how the vehicle will behave and where it might end up during the mission (McPhail, 2006). The autonomy of underwater vehicles is still at a level that keeps onboard operations decisions within well understood limits and hence the vehicle's track will be known should faults occur, although this is likely to be relaxed as user experience increases. Vehicles can still be lost under present day operating scenarios.

In the future, certain organisations may develop skilled user services and training that can be accessed by new users or potential users. This may involve AUV awareness courses through to full operating services for vehicles, similar to companies that have sprung up around the operations of remotely operated vehicles (ROV) for the offshore industry. A distinction may develop between the present situation, where most operators are 'intelligent users' and/or vehicle developers through to users who want to make use of AUVs as a piece of 'black box equipment'.

Online services may be used by the various internationally based AUV operations teams to share information and solve problems. There may be a place for an online community information repository for AUV technology and sensor information, such as that provided by tools such as Wiki and Plone and websites such as Wikipedia.

3. Funding

Funding of an AUV operation has to include that required for the initial capital purchase, operating funding for missions, insurance, maintenance and repairs, as well as upgrades and eventual replacement. Besides the actual AUV, capital purchase may include required manufacturer's training; computer hardware; data transmission services (e.g. Iridium); basic recovery equipment (e.g. ranging transponder); a set of basic spares and possibly specialised supporting equipment (e.g. pump for evacuating vehicle chamber or a battery charger).

Operating funding has to include that needed for personnel, transport of the AUV and personnel to site, and support craft. Operational funding requirements will vary with the location of the missions. Ones that are done from a shore based location with a small support craft will require lower operating funding than a complex oceanic mission using a ship many miles from the home base, such as in the Antarctic. Operations that make use of some part-time or contract personnel – although potentially problematic in

terms of team training – may be cheaper in the short term than operations that involve a full-time dedicated team. Part time personnel may include full time staff drawn from other projects/duties.

AUVs are often funded through major research equipment grant applications that are primarily for capital items and have less emphasis on the needs for operating funding. This can be a trap for both new and experienced users, as under these programmes it is possible to fund equipment without having a dedicated team in place for the new item. The track record (credibility) of the team with its funding authorities and clients can be an issue. Experienced teams with a past history of successful missions and the publication of new scientific knowledge may find continued funding easier to achieve than a new team.

Operational funding needs may be difficult to estimate for the new user. Science programme applications with the vehicle and/or third-party use of the vehicle by users who can pay a daily rate for access need to be fully costed. The costing sheet used by the UK Ocean Research Services (UKORS) at Southampton (now NMF Sea Systems) is an example of a systematic approach for determining operational costs (see Figure 3, next page).

Anecdotally, approximate operational charges for cost recovery vary between vehicles:

- €5000 per day for the IFREMER Explorer excluding ship costs, but including two AUV personnel (Rigaud 2006)
- £8700 per day for Autosub including coastal research ship costs
- Up to $10 000 (Canadian) per day for the *MUN Explorer AUV* (estimate of future operations).

These costs are approximate, but they give an order of magnitude of the expected costs of operation of one of the larger survey class AUVs.

Operators need to be aware that certain AUV related equipment – such as the higher end inertial navigation units and certain batteries – may involve complex import and export regulations when moving a vehicle between international destinations, and overcoming such issues may involve considerable hidden costs.

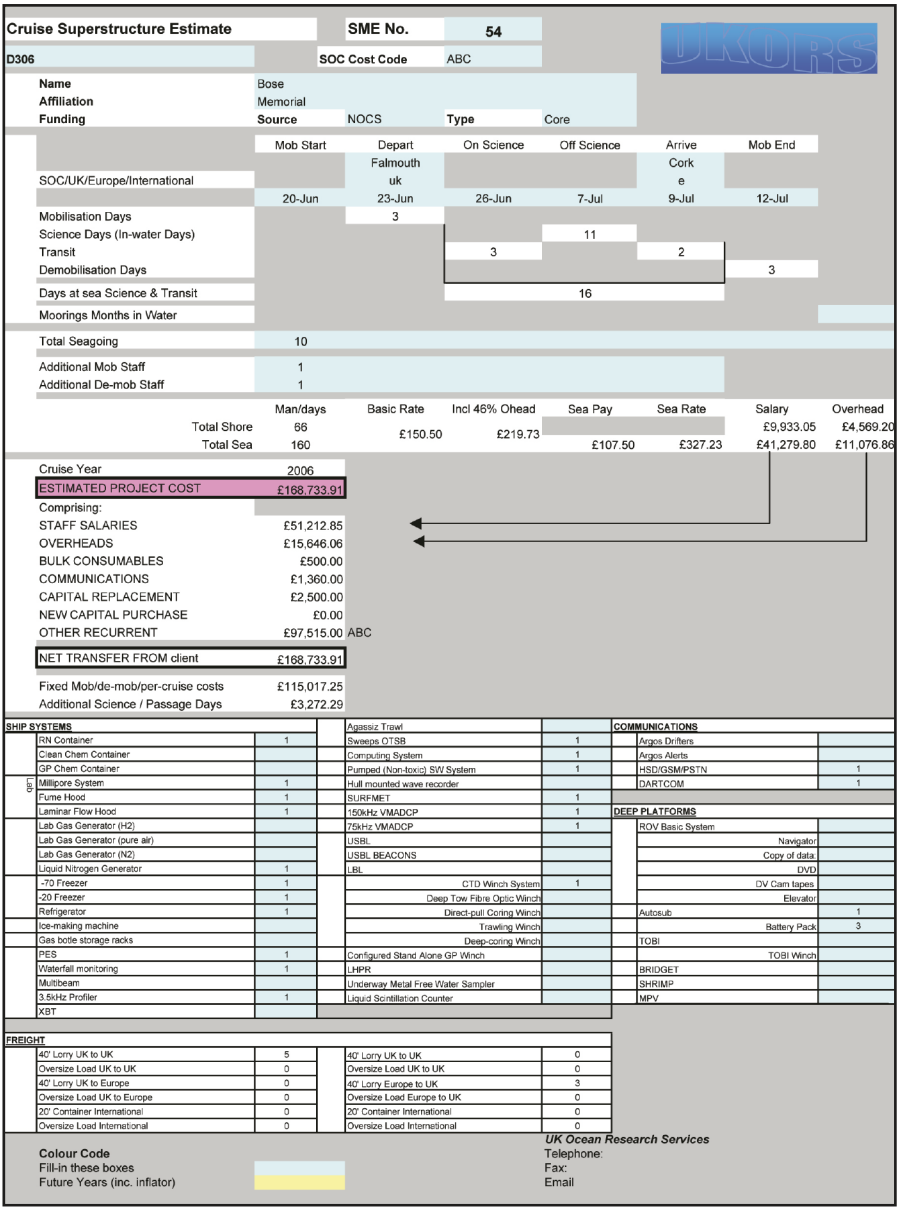
Estimated costs for maintenance, repairs and upgrades can be obtained from manufacturers. Common expenses include sensor calibration, battery changes and any number of upgrades. A manufacturer should provide warranty, and a service or maintenance agreement with the manufacturer may be the most economical for 'black box users'. The responsiveness of the manufacturer to requests for information and prompt repair turnaround is important to a good operator/manufacturer relationship.

4. Insurance

AUV insurance is an issue for operators, as AUV operations are seen by underwriters as a relatively high-risk activity. There have been several total losses of AUVs experienced to

date. Insurance was the subject of a recent seminar held by the Engineering Committee on Oceanic Resources (ECOR) Specialist Panel on Underwater Vehicles and a position paper, which will include several case studies, is in preparation following that meeting

Figure 3: Example UKORS (now NMF Sea Systems) costing sheet



Cruise Superstructure Estimate — SME No. 54 — UKORS

D306 — SOC Cost Code ABC

Name	Bose
Affiliation	Memorial
Funding Source	NOCS — Type: Core

	Mob Start	Depart	On Science	Off Science	Arrive	Mob End
		Falmouth			Cork	
SOC/UK/Europe/International		uk			e	
	20-Jun	23-Jun	26-Jun	7-Jul	9-Jul	12-Jul
Mobilisation Days		3				
Science Days (In-water Days)				11		
Transit			3		2	
Demobilisation Days						3
Days at sea Science & Transit				16		
Moorings Months in Water						

Total Seagoing	10
Additional Mob Staff	1
Additional De-mob Staff	1

	Man/days	Basic Rate	Incl 46% Ohead	Sea Pay	Sea Rate	Salary	Overhead
Total Shore	66	£150.50	£219.73			£9,933.05	£4,569.20
Total Sea	160			£107.50	£327.23	£41,279.80	£11,076.86

Cruise Year	2006
ESTIMATED PROJECT COST	£168,733.91
Comprising:	
STAFF SALARIES	£51,212.85
OVERHEADS	£15,646.06
BULK CONSUMABLES	£500.00
COMMUNICATIONS	£1,360.00
CAPITAL REPLACEMENT	£2,500.00
NEW CAPITAL PURCHASE	£0.00
OTHER RECURRENT	£97,515.00 ABC
NET TRANSFER FROM client	£168,733.91
Fixed Mob/de-mob/per-cruise costs	£115,017.25
Additional Science / Passage Days	£3,272.29

SHIP SYSTEMS					COMMUNICATIONS	
	RN Container	1	Agassiz Trawl		Argos Drifters	
	Clean Chem Container		Sweeps OTSB	1	Argos Alerts	
	GP Chem Container		Computing System	1	HSD/GSM/PSTN	1
QBT	Millipore System	1	Pumped (Non-toxic) SW System	1	DARTCOM	1
	Fume Hood	1	Hull mounted wave recorder			
	Laminar Flow Hood	1	SURFMET	1		
	Lab Gas Generator (H2)		150kHz VMADCP	1	DEEP PLATFORMS	
	Lab Gas Generator (pure air)		75kHz VMADCP	1	ROV Basic System	
	Lab Gas Generator (N2)		USBL		Navigator	
	Liquid Nitrogen Generator		USBL BEACONS		Copy of data	
	Liquid Nitrogen Generator	1	LBL		DVD	
	-70 Freezer	1	CTD Winch System	1	DV Cam tapes	
	-20 Freezer	1	Deep Tow Fibre Optic Winch		Elevator	
	Refrigerator	1	Direct-pull Coring Winch		Autosub	1
	Ice-making machine		Trawling Winch		Battery Pack	3
	Gas bottle storage racks		Deep-coring Winch		TOBI	
	PES	1	Configured Stand Alone GP Winch		TOBI Winch	
	Waterfall monitoring	1	LHPR		BRIDGET	
	Multibeam		Underway Metal Free Water Sampler		SHRIMP	
	3.5kHz Profiler	1	Liquid Scintillation Counter		MPV	
	XBT					

FREIGHT				
40' Lorry UK to UK	5	40' Lorry UK to UK	0	
Oversize Load UK to UK	0	Oversize Load UK to UK	0	
40' Lorry UK to Europe	0	40' Lorry Europe to UK	3	
Oversize Load UK to Europe	0	Oversize Load Europe to UK	0	
20' Container International	0	20' Container International	0	
Oversize Load International	0	Oversize Load International	0	

Colour Code
Fill-in these boxes
Future Years (inc. inflator)

UK Ocean Research Services
Telephone:
Fax:
Email

(Griffiths *et al.*, 2007). It has been said that the best insurance may be to have a second identical vehicle available to hand to replace a vehicle during its operation should damage or a loss be experienced (Ferguson, 2006). Some insurance options are listed as follows:

- AUV insurers: The Leviathan Facility are perhaps the only underwriters who specialise exclusively in specialised marine equipment insurance for ROVs and AUVs, but other companies do underwrite AUVs as part of their portfolio. Brokers include companies such as Willis and Waveney Insurance.
- Presently practical rates vary approximately in the range 6–20 percent of capital cost per year depending on the risks involved, the type of operation, the experience of the operating team, etc. Rates are much more in high-risk situations, such as AUV missions under glacial ice, but the operator has to address issues of whether to proceed with insurance if rates exceed 15–20 percent. Rates up to 95 percent have been quoted, which is an indication that the underwriter would rather not carry the risk.
- Self-insurance may be the only affordable prospect, especially for new teams, but the question has to be asked if it is realistic. Can the operator withstand the risks of operating without insurance? What are the risks of losing the vehicle, and can it be recovered if lost? What are the risks of a total loss, and can the operator carry that risk? A risk management process tuned to the needs of AUV owners and operators is described in Griffiths and Trembanis (this volume).
- Operators may be asked by an underwriter to carry part of the loss themselves, either through a hefty deductible or through a form of co-insurance, especially for launch/recovery operations which are seen to be of particularly high risk. An operator must act as a prudently un-insured operator, since the deductible would cover many repair costs associated with minor damage or recovery costs associated with a loss in relatively benign conditions. If vehicle operations are in relatively shallow water that can be reached by divers and/or a small ROV, recovery costs following a loss may be less than the deductible of many policies.
- The operator should be covered for indemnity and liability, even if insurance cover for loss or damage is not purchased. Similarly, purchasing cover for damage or loss in transit may be advisable.
- Costs to repair damage or recover from a partial loss may be large, and from an operator's perspective a total loss/write off might be preferable to rehabilitation of the existing vehicle. The final decision would be based on the surveyors used by the underwriters to assess damage.

To minimise insurance costs, new users must establish a reliable operating track record to achieve credibility for safe vehicle operations. This can be assisted by development of in-house operating procedures and protocols, including the development of operations manuals demonstrating competence to brokers and underwriters. New users should demonstrate that their operators have been trained through a manufacturer's training

programme and other means. There may be operating scenarios, or dogmas (Rigaud, 2006), that can be implemented by a user to address a particular environment: for example the IFREMER strategy to not return to the surface on recovery until the surface vessel is nearby in order to avoid collisions between fast surface vessels and the AUVs.

For a new user, self-insurance may be necessary, as cover may not be available at an acceptable price, but this is a risky option. If possible the user should build up a replacement/recovery fund to address losses. Such accumulation and carry over of funding can be difficult, if not impossible, in many public sector organisations. The fund will need to address the scope of operations to track and recover the vehicle.

There is a danger that new inexperienced users might skew damage/loss statistics if they act irresponsibly. It is of benefit to all AUV operators to share information and assist with training and operating experience of new users. Minor damage during launch and recovery may be under-reported to insurers (e.g. antennae, fins, props) since operators would expect to repair such items in-house prior to the next operation.

The industry is some way away from the expendable AUV, although the small glider vehicles come close to achieving this. Expendable AUVs may be one way of addressing the insurance issue from an operator's perspective. It is difficult, however, to see how the larger AUVs with their ability to carry large and expensive equipment, such as the relatively powerful multibeam echosounders, can fit into this category.

5. Safety

Safety includes damage/loss of the AUV itself and/or damage/loss during launch and recovery, as addressed in the previous section. Safety also includes damage and loss to others, including support and other vessels, operating personnel, other ocean users, etc. Collisions between the AUV and other vessels are an issue. Safety can be alleviated to some extent through adherence to operating protocols, but at present there are no generally accepted regulations for the use of AUVs in the oceans (Brown and Gaskell, 2000).

New users must consider the detailed operation and protocols, e.g. Dering *et al.* (2000). The team should be trained in basic seamanship and in general safety procedures, such as use of hard hats, life jackets and safety harnesses. Attendance at approved sea survival courses that meet STCW95 requirements may be needed. Training in gun operation, safety on surface ice and cold weather survival are advised for polar missions. There are large amounts of stored energy in an AUV, thus electrical safety procedures in a wet environment are required. For launch and recovery, high loadings with lifting gear occur and operators may be unaccustomed to the vessel, which may be a vessel of opportunity. Recognising these hazards, it may be advisable to hold joint training exercises between the AUV operators and the ship crew in calm waters beforehand. Naval architectural aspects, such as stability, can be important if the AUV is large and the vessel relatively small (Figure 3).

Figure 3: Support ship stability and handling issues may result if the AUV is large relative to the vessel

Legal aspects of operation are likely to become an issue as more AUVs are in operation (Brown and Gaskell, 2000). The current legal situation for AUV operations is still not clear and is likely to be different in various countries. Experience at one location may not be transferable to another country. Safety of personnel is paramount everywhere, but there may be different expectations relative to liability in different countries. The sources of legal and safety advice are not clear.

6. Summary

This paper on the needs of new users of AUVs addresses issues that will be of concern to all operators of these vehicles. The emphasis has been to provide answers to some of the main questions facing a new AUV operator. In some areas, such as legal aspects of operation, little information is available and recourse has been made to pointing out issues rather than attempting to provide answers. The AUV world is growing and vehicles are becoming mature; their capabilities are becoming recognised as valuable monitoring and research tools to both the scientific community and the offshore and ocean engineering industry. Their use is of particular value in operations and locations where it is difficult or impossible employ other types of technology. As confidence with their operation grows, their autonomous operation has huge potential for independently undertaking lengthy survey and monitoring missions.

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Launch and Recovery of Autonomous Underwater Vehicles in Polar Regions

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Abstract
Launch and recovery has proved to be one of the areas of greatest risk within the overall operations of autonomous underwater vehicles (AUV). For work in polar regions, in addition to the hazards of handling the vehicle from the ship, working under sea ice and ice shelves brings new challenges when one considers that a vehicle launch is not complete until the vehicle has begun its mission, and recovery begins with wanting to rendezvous with the vehicle. The Autosub Under Ice (AUI) programme has sought to mitigate those risks by developing: systems and procedures that allow the AUV to be deployed in seas with substantial ice cover; an ability to overcome large water density changes that would otherwise affect its ability to dive and control depth; and systems to guide the vehicle back to the ship under its own control. These developments have enabled Autosub to greatly increase the effective mission time and make greater use of ship time.

1. Introduction

The launch and, especially, the recovery of relatively fragile vehicles in deteriorating sea conditions have at times taxed the seamanship of the ship's crew to the full. As AUVs started to become more commonplace during the late 1990s a store of experience, anecdotes and statistics began to grow, highlighting the inherent risk of damage, sometimes leading to insurance claims. Griffiths *et al.* (2007) quote one underwriter that offers co-insurance for the period of launch and recovery, that is, risk is shared for that part of the operation. The use of AUVs in extreme environments, such as under polar ice shelves, has added to the complexity of operations, especially in monitoring the location of the vehicle and maintaining choice over where to recover the vehicle.

2. Drivers for Improvement

There are a number of drivers that require the process of launch and recovery to be improved:

- **Reduce insurance premiums:** The NERC funded AUI programme illustrated the risk of loss when the insurance premium was so high as to be unacceptable (Griffiths *et al.*, 2007). Such is the number of claims associated with the vehicle recovery that future insurance may specifically exclude recovery.
- **Reduce the risk of losing capital equipment:** The recovery of a stranded AUV from the seabed may involve the expense of a remotely operated vehicle (ROV) operation, while recovery from under an ice shelf may easily exceed the value of the vehicle and sensor suite. As well as financial loss, it is likely to affect the prestige of the host operator/owner and future programmes.
- **Increase the probability of obtaining the data:** The AUI was funded as a high risk–high gain programme. The mission before the vehicle was lost under the Fimbulisen in February 2005 proved the data was exceedingly interesting and showed features of the ice underside that were unexpected and previously unseen (Nicholls *et al.*, 2006). The loss of the vehicle would not have been so bad if it had not also meant the loss of the data collected during the fated mission.
- **Improve the reputation of the AUV community:** The use of AUVs in science and commercial surveys is still young and stories of failure of one AUV impacts the reputation of the whole. We still need to prove that AUVs are a viable and advantageous way of data-gathering in polar waters.
- **Reduce environmental impact:** Potential environmental impact to sensitive areas forms part of the assessment and may make the case to undertake new programmes more difficult. Many of the issues arising from working in the area covered by the Antarctic Treaty are outlined in Brown and Gaskell (2001).
- **Improve the operational availability:** Ship time on station is very limited and repairs at sea reduce the AUV operational time significantly. Damage incurred during launch – especially if undetected – may cause problems later. Science cruises often intertwine with several disciplines and unexpected difficulties, e.g. a protracted time to locate the AUV, impedes other work.

3. Summary of Handling Methods Used

3.1 Ship-Based Method

The most common methods of handling AUVs to and from the host ship are in the main variations of methods tried and tested over many decades of offshore operations and oceanography. Assuming the AUV has a line to be caught, the AUV line can be grappled as the ship draws along side the vehicle and a long line attached to be winched in by recovery gantry or A-frame equipment on the rear deck. This is akin to the recovery of moorings.

A variation successfully used by C&C Technologies with the HUGIN family of vehicles is a stern ramp lowered into the water and the vehicle winched up the slope; this is similar to methods used for the 2.5 tonne GLORIA vehicle operated by the Institute of Oceanographic Sciences (IOS) in the 1980s. Where an initial line deployment system is not present some operators, particularly in coastal waters or for small AUVs, still rely on deploying a small boat or diver to make the initial attachment. With increasing concerns over health and safety, this is becoming less common. Figures 1 and 2 illustrate some typical systems.

Figure 1: The IOSDL towed GLORIA vehicle (left) and HUGIN 3000 AUV, both utilising a stern ramp for a smooth transition to the ship

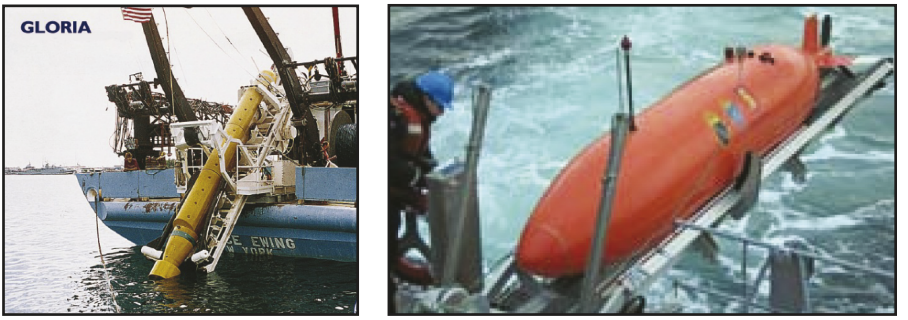
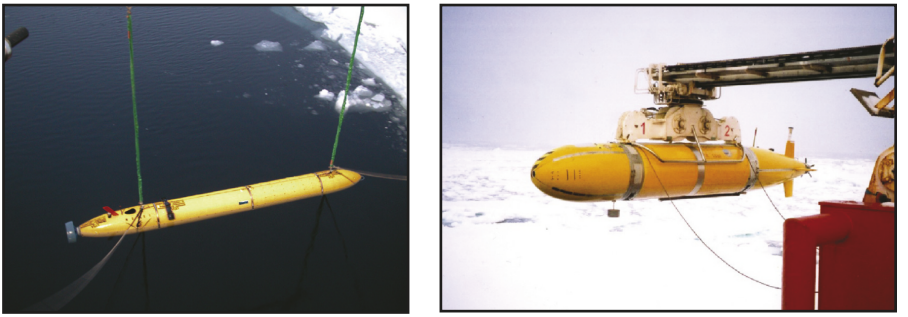


Figure 2: Two examples of AUVs being launched using similar techniques for under-ice operation Left: MBARI Dorado vehicle in use in Arctic regions; Right: the National Oceanography Centre Autosub in the Antarctic on an extendable boom to lift the vehicle out of the water



Many other more complex systems have been proposed and some have been built: for instance recovering vehicles from the ship's side into bespoke hangers or building the ship with a substantial stern ramp for the generic recovery of small boats and UUVs.

3.2 Ice-Based Method

A major ice project carried out with an AUV was by International Submarine Engineering Ltd with the *Theseus* vehicle (Ferguson, 2003; Hopkin, this volume). This ambitious task – to lay a fibre-optic cable beneath the ice – was carried out essentially without any ship support. Instead, the base of operations was set up on the ice at Jolliffe Bay, Ellesmere Island, Canada. The vehicle was flown in parts by helicopter to the base camp, consisting of an 11 m x 20 m WeatherHaven tent with infrastructure mounted on the ice for lifting and manoeuvring the vehicle. *Theseus* was launched and recovered through an ice hole, with some human intervention during the final stages of navigation.

Another example of working in this way is described in the 'Below Ice Environment Laboratory Using an AUV' proposal (BELUGA) as part of the International Polar Year (IPY) (Bose *et al.*, 2006). The Memorial University of Newfoundland prosed using its recently purchased ISE 4 m long *MUN Explorer AUV* through an ice hole for studying water quality, ice thickness, methane levels and seabed topography and biology. The base camps proposed were similar to those created by ISE at Joliffe Bay, obviating the need for research ships. The vehicle will also be used for environmental surveys in the province of Newfoundland and Labrador.

Operating from an ice camp may allow longer periods of stay on the ice by not requiring a ship in a fixed location, and it allows for deeper penetration into ice bound areas. This is a significant advantage since, as will be described in the following section, getting the AUV to and from the ice can take up a large amount of the AUV's endurance.

4. Specific Problems Related to Polar Regions

4.1 Ice Cover

While many handling problems in open oceans are a result of high sea states, regions near ice shelves or within pack ice tend to be calm, thus the main difficulties in polar regions arise not from waves but the ever-changing ice conditions. During the first Autosub campaign in the Antarctic (Brierley *et al.*, 2002), the team tried to work a policy of launching and recovering the vehicle in areas which were virtually clear of ice to give enough space for the vehicle to do its surface run prior to diving (a surface speed of about $1.5 m.s^{-1}$ is needed for the sternplanes to overcome the vehicle buoyancy). The propeller is especially vulnerable at this time, evidenced in Figure 3 showing all the propeller blades being cleanly broken off by colliding with a single small piece of ice

The problems of ice cover were compounded if the wind was from the south blowing ice away from the ice pack. The launch and recovery position was tens of kilometres away from the area of interest and a good proportion of battery energy was expended simply getting to the ice edge.

Figure 3: All five-propeller blades broken while attempting a surface run in seemingly ice-free conditions

For subsequent campaigns, a sink weight and release system was developed allowing the vehicle to be launched in any clear patch of water. A 20 kg steel weight slung from the underside would begin to sink the vehicle (Figure 2); at a predetermined depth, the weight would release and the propulsion motor would start. The whole autonomous mission from that point would be carried out submerged.

Since the sink weight system can potentially permanently sink the vehicle and is dependant on a power source, electronics, software, mission programming, connectors and mechanics, a safety release is fitted between the weight and the programmable release. This is a disposable passive device operating on hydrostatic pressure set to release at a depth two or three times the programmed release depth. The system greatly enhances the effectiveness of under-ice work by facilitating work close to the ice edge and placing the AUV into a convenient patch of ice-free water. However, such launches require swift communication between the bridge and aft deck. Small pieces of ice or small ice floes (but still weighing several tonnes) can move around the ship surprisingly quickly, and seconds count when choosing one's moment to launch in order to release the AUV.

4.2 Water Density Gradients

For AUVs such as *Theseus* with active buoyancy control systems, the vertical density gradients encountered in the Arctic were not a serious issue (Ferguson, 2003). However, where an AUV does not use active buoyancy control, difficulties can arise. For example, Autosub is ballasted to be 8 to 12 kg positively buoyant in water (0.4 percent of its weight in air). Final ballast adjustments are usually made on the working site after taking some water density measurements using conductivity, temperature, and depth (CTD) data from the ship or a simple hydrometer in a bucket of water.

When working close to the glacier in the Kangerdlugssuaq fjord off the coast of Greenland, we noted a significant difference between the hydrometer measurements taken from surface water and the ships readings from water taken beneath the hull (draft of 6 m). In the very still waters, the fresh water running from the glacier created a freshwater layer with a density difference of 4 kg/m^3 between samples taken from undisturbed water at the bow of the ship and those taken from the stern which had been mixed by the movement of the ship (Figure 4). This density difference created a 10 kg increase in buoyancy for the vehicle at its working depth and care had to be taken to ensure the vehicle was able to control its depth for all conditions.

The solution adopted by the Autosub team was to fit winglets slightly aft of the vehicle's centre of gravity to create addition downward force while moving (Figure 4 and Table 1). These proved effective and had the added benefit of reducing body pitch angle and drag. The graphs showing the lift and drag characteristics are from the software package VisualFoil (Figure 5).

Winglets Fitted for Under-Ice Work Close to Land	
Section	14% NACA
Wing Span (excluding the body diameter)	310 mm
Wing Chord	254 mm
Angle of Attack	5 degrees
Vehicle Pitch Angle (w/o winglets)	3 degrees
Vehicle Pitch with Winglets	1 degree
Estimated Downforce at 1.5 m/s	120 N
Estimated Drag due to Winglets at 1.5 m/s	3–4 N

Table 1: Details of the winglets fitted to Autosub to create addition downforce

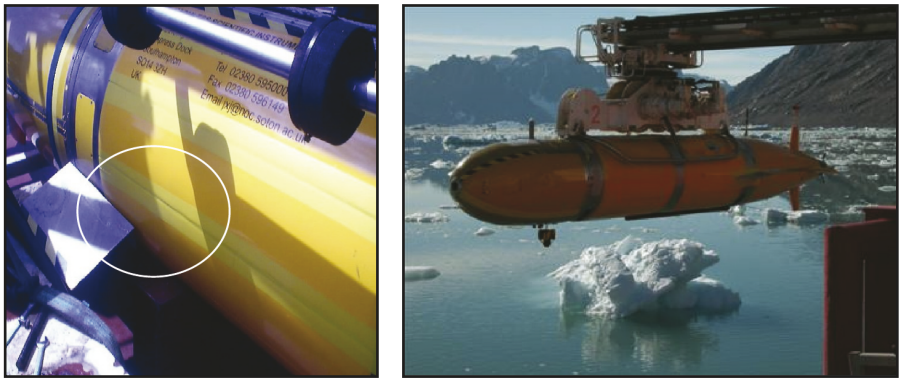


Figure 4: Autosub working off the coast of Greenland. The combination of very still water and freshwater runoff created unusually steep water density gradients
Left: Aluminium winglets (circled) fitted to the side of Autosub to create additional down-force. The spherical homing transducers can be seen just above the sink weight
Right: The 20 kg weight can be seen hanging off the nose section

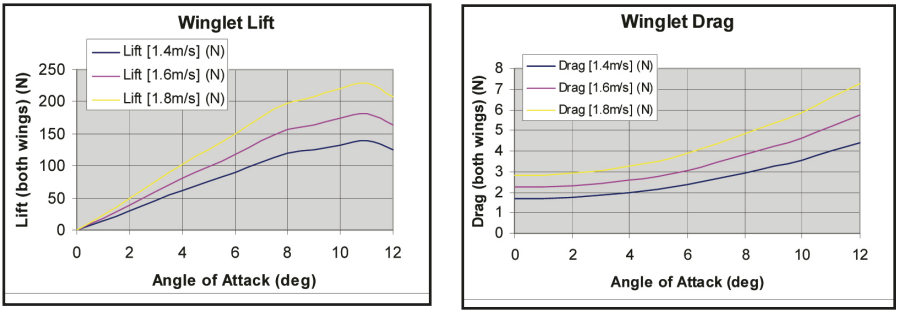


Figure 5: Estimates of lift and drag forces from winglets

4.3 Surfacing in Ice

Most AUVs have transmitting and receiving antenna mounted on top for communications and navigation. For Autosub these are two Argos satellite transmitters for vehicle location, an Ethernet radio for downloading missions and data and global positioning system (GPS) for vehicle position. These are vulnerable during the final stages of the recovery process (after which they can be replaced or repaired if necessary). For under-ice work, they may be damaged by the ice before the vehicle has been located and could result in vehicle loss simply because it could not be found.

Figure 6 shows two occasions where AUVs have surfaced in ice; the water may have been clear when the site for surfacing was chosen, but conditions changed noticeably in a few hours. Although the ice cover was only very light, it demonstrated how easily antenna could be broken by colliding with pieces of ice while surfacing and how quickly the antenna can become smothered. Autosub is particularly dependent on the Argos transmissions for location at the end of the mission and a glass-fibre reinforced plastic (GFRP) tube was made to fit over the forward aerial to give some protection against ice damage. The experience highlighted the need to remotely control the vehicle surfacing at the end of the mission, rather than trying to second-guess ice conditions at the mission programming stage.

Figure 6:
Two occasions where AUVs have surfaced in different forms of light ice cover
Right: Maridan among first year floes
Below: Autosub under nilas or grease ice

4.4 Homing Systems

A preferred way to surface the vehicle at the end of the mission is to have control over the surfacing position. In principle, this could be done by interacting with the mission management while under water to tell the vehicle its final surfacing waypoint. In practice, this introduces a level of complexity and variability in the acoustic communications that are prone to patchy reliability.

The more robust solution, independent of the acoustic data communications, has been adopted by fitting three homing hydrophones to the underside of the vehicle (Figure 7). An array of two ceramic ring transducers is lowered 50 m over the side of the ship to transmit a homing signal, enabling the source to be triangulated via the hydrophones on the AUV. Autosub uses the inferred direction to control its course to head towards the beacon. The vehicle mission management continuously listens for updated beacon signals and corrects its course accordingly. If it fails to receive a signal after ten seconds, the vehicle will hold its position until locating the homing signal once more. This prevents it from proceeding indefinitely on a fixed heading. While the vehicle is homing on to the ship, the range, depth and heading is being acoustically monitored by the team to choose a suitable moment to give a surface command.

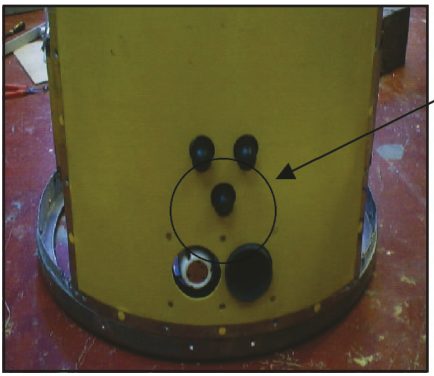


Figure 7:
Three hydrophones mounted on the underside of Autosub enables the vehicle to triangulate the direction of a homing beacon

4.5 Emergency Location System

In the event of mission failure, Autosub has been fitted with an emergency acoustic beacon to aid location of the vehicle. An array of two ceramic ring transducers, similar to the ship's transducers used for homing, are housed in the AUV tail section. The mission management is programmed to recognise mission threatening conditions, e.g. the mission has continued too long. Under these conditions, the beacon is dropped by the solenoid on a 15 m cable to hang below the vehicle, reducing the effect of surface acoustic reflections. The beacon uses a 0.8 s chirp spanning 20 Hz at a centre frequency of 4.504 kHz, providing sufficient acoustic propagation through water to operate over distances of tens of kilometres.

The beacon on the vehicle contains an accurate clock (0.1 s/day drift) to trigger the transmission of acoustic pulses at 1-minute intervals. This clock is synchronised to the GPS clock onboard the ship, allowing the time interval between transmission and reception (and thus range from submarine to ship) to be measured. Under normal conditions the emergency beacon is powered directly from the main Autosub battery pack. If this should fail, the beacon switches over to an internal battery able to power the device for many months. The position of the vehicle can be calculated by triangulation from a number of ship locations.

5. Conclusion

The scope of launch and recovery is often limited to the vehicle's physical handling to and from the sea. This paper illustrates this and other important issues in starting the mission safely and locating the vehicle at the end. The Autosub development of the sink weight release system (allowing launch in small clear patches of water); small wings (giving the ability to overcome large water density differences); and the homing and location beacons (assisting retrieval from inaccessible places) have been developed specifically for AUI campaigns to reduce the risk of vehicle and data loss.

AUV work in polar regions still remains high-risk, and there is scope for developing other strategies or vehicles for such work. Disposable vehicles capable of sending back the data from beneath the ice would be attractive, perhaps via a fibre-optic link. An alternative modus operandi is to control the vehicle via an acoustic modem or use a network of moored, low frequency, acoustic stations to assist the navigation of AUVs (Seattle Workshop, 2006; Lee *et al.*, 2006).

Increased demand of operations from an ice shelves may make the idea of a tethered vehicle more viable, for instance a hybrid ROV and AUV where the vehicle carries its own power source but is controlled remotely by a human in the loop. Such a vehicle, although not destined for under-ice work, is being developed at the Woods Hole Oceanographic Institution. Named *Nereus*, this will be a hybrid ROV/AUV (known as an HROV) capable of being operated autonomously or with a human in the loop.

Although the problems in achieving successful operation are considerable, under-ice surveys remains one area of important oceanographic work that can only be done by AUVs. The AUI programme has shown there is much to learn and discover by carrying out a survey as oppose to single point measurements through the ice. Further developments and honing of existing methods are capable of delivering a considerable wealth of new knowledge on the under-ice environment in addition to what has already been achieved.

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Autonomy and Collision Avoidance

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Abstract
The degree of autonomy exhibited by autonomous underwater vehicles (AUV) that are operational today is relatively low and varied. Many vehicles are constantly escorted by, and in constant communication with, a support ship, while only a few are operated in truly autonomous 'over the horizon' scenarios. The autonomy of all these vehicles tends to consist of a simplistic event-driven waypoint-following behaviour. The reasons for this are practical rather than technological. An AUV that is relatively straightforward to operate, and does more or less exactly what it is told, is generally more likely to be ready and in a working state at the prescribed time and place for deployment. However, the use of AUVs is becoming more widespread, and the environments in which they operate and the tasks they perform are becoming more challenging. Consequently, an increase in autonomy is inevitable. This chapter looks at the characteristics of autonomy that are important for AUVs and explores the state of the art in operational vehicles. Collision avoidance is treated as a specific example of autonomy and, as such, is dealt with in the course of the following discussion. Conclusions are formed around the perceived gaps in technology that pose problems for operations in extreme and under-ice environments.

1. Introduction

The meaning of autonomy is not used consistently across the various disciplines that are involved in the development and operation of AUV technology. For the artificial intelligence (AI) community, autonomy has implications that relate to self-determination and an ability to learn through experience gained from sensing and acting in the real world (Russell and Norvig, 1995). In the offshore industry, autonomy refers to systems that are self-contained and self-sufficient, being able to operate without direct connection to a support platform or mother ship; this may simply be a system that is powered by batteries and logs its own data. Most AUVs in operation to date are certainly autonomous as far as the offshore industry is concerned, but as most are relatively simple scripted waypoint-following vehicles, it is claimed that they are not truly autonomous by the AI community. It is generally suggested that their behaviour is largely deterministic.

Indeterministic behaviour is, by definition, unpredictable and can cause problems for operators of AUVs. In many cases a simple waypoint-following vehicle will execute a survey and complete its mission in a predicable period of time, while a more 'intelligent' or more autonomous vehicle might make decisions that significantly effect the outcome of its mission and hence arrival time at a rendezvous. Although it may easily be claimed that the priority assigned to a rendezvous task should be set as one of utmost significance in an autonomous mission, the added complexity of having to remember to set that priority may be prohibitive to simple operational procedures. Other complexities arise from an autonomous system making the wrong decision, which may result in the costly loss of data coverage and waste of time.

One important area where enhanced autonomy is being utilised is that of collision avoidance. AUVs have been equipped with reactive control behaviours that use sensed information of the local environment to avoid collisions and obstacles within the course of their scripted waypoint tracking. In addition to the collision avoidance behaviour, other autonomous control behaviours are being developed which are fundamental to furthering the mission capabilities of AUVs, such the automated nested survey system that is operational in the Woods Hole Autonomous Benthic Explorer (ABE) vehicle. Other more advanced forms of autonomy, such as autonomous mission planning, exist as research demonstrators and are yet to appear in a sufficiently robust and tested form to be adopted by the ocean science and offshore survey communities.

Irrespective of the nature of autonomy, during the discussion held during the Masterclass in AUV Technology for Polar Science it was largely agreed that the basic requirements for an AUV are to be reliable and robust. Without this basic operational principal, there is little benefit to including more complex control strategies associated with higher levels of autonomy. The significance of reliability in AUV systems is dealt with by Griffiths and Trembanis (this volume).

The topic of autonomy is extensive and multidisciplinary, thus the following discussion is necessarily restricted to an overview that addresses key aspects of autonomy relevant

to the AUV and ocean science community: survey enhancement, vehicle robustness, vehicle protection and operational simplification.

2. Where Autonomy Fits In

Given that autonomy can be described as being an emerging characteristic of the many facets of an AUV's systems and activities, it is instructive to view the diagram in Figure 1, which illustrates a common interpretation of an autonomous vehicle control system (Gat, 1998).

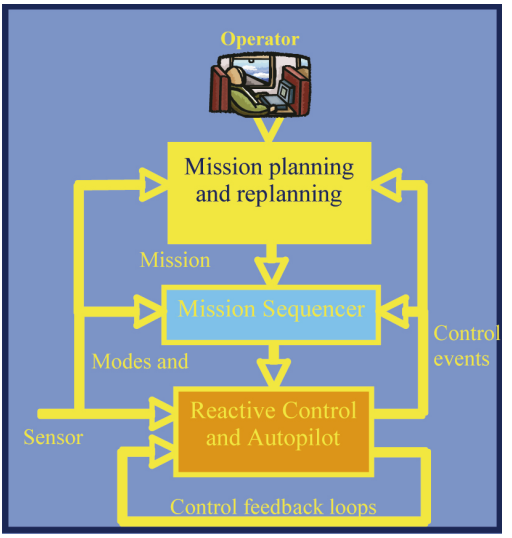


Figure 1: Showing a three-layer control structure of an autonomous vehicle

It is a three-layered hierarchical architecture with the real-world interaction occurring at the bottom, and higher, more abstract, non-real-time processes taking place at the top. The bottom layers represent the implementation of continuous control loops that realise a form of autopilot functionality and reactive control behaviours. The middle layer stores and executes, in sequence, the mission plan while the top layer performs planning and re-planning tasks. There are few if any operational AUVs to date that autonomously utilise the top layer during a mission.

The remainder of this chapter looks at autonomy and where it may be useful in various aspects of building and operating an AUV.

2.1 Survey Enhancement

AUVs have, until recently, been restricted to performing relatively simplistic surveys, with missions consisting of anything from simple transects along a track between two waypoints to a multi-, parallel track or lawnmower pattern. Depth control has consisted of either depth relative flight or a terrain following mode. More complex object relative control using acoustic or visual feedback has rarely been utilised. It is most likely the case that the former technique will continue to be central to the operation of AUV surveys. However, given that an AUV has a limited range, and that the operator may not have sufficient prior knowledge of the work site, it may be desirable to provide an AUV with an ability to dynamically optimise the mission's navigation.

There are now examples of AUVs being used operationally with reactive control behaviours that are able to adapt pre-programmed mission surveys depending on updated sensory information.

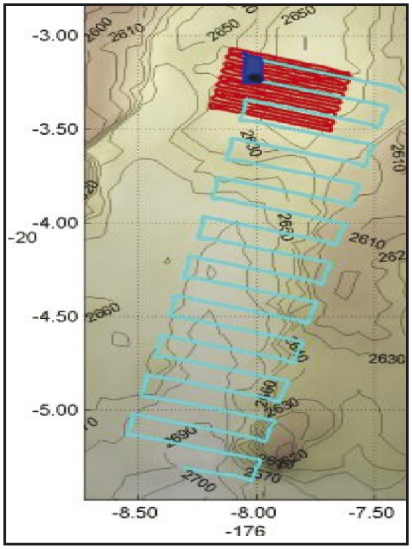
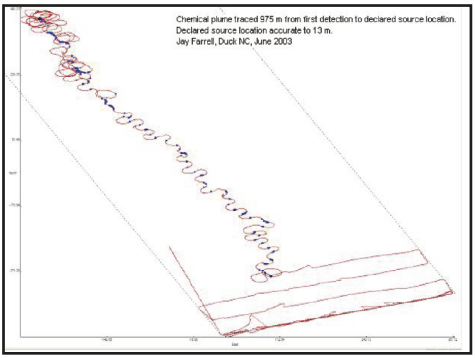
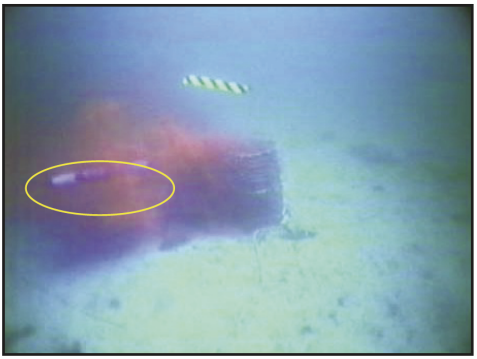


Figure 2: Woods Hole Oceanographic Institution's ABE (above) and the track of a nested survey showing three levels of track spacing (right) – Courtesy WHOI

Figure 3 (below): Chemical plume tracking navigation (top) and the REMUS vehicle (highlighted in yellow) within the plume (bottom) – Courtesy of SPAWAR and University of California, Riverside





The ABE (Figure 2), operated by the Woods Hole Oceanographic Institution, has a long and successful track record of deep ocean floor survey. It has recently been operated with an enhanced control ability to opportunistically modify the resolution of its survey pattern depending on dynamically sensed information (Yoerger *et al.*, 2005). This behaviour has been used for locating and surveying vent plumes on mid-ocean ridges. Figure 2 shows how a standard lawnmower survey pattern is generated with decreasing line spacing in order to concentrate the AUV's effort in an area of high interest.

The US Space and Naval Warfare Systems Command (SPAWAR), in conjunction with the University of California, Riverside, has been running open-water experiments with a plume tracking behaviour on a Hydroid Remus AUV (Farrell *et al.*, 2005). The vehicle initiates a lawnmower pattern survey (Figure 3) until sufficient sensory signal is detected,

at which point a homing behaviour is entered that follows a chemical concentration gradient to its source. If the chemical trace is lost, then the lawnmower survey pattern is re-entered.

2.2 Vehicle Robustness

An AUV must be able to work consistently and, if necessary, be able to accurately repeat its mission. It must be available for work and have a minimal impact on other operations being undertaken by its support vessel. In particular navigation must be accurate (as defined by the mission requirements) and able to position the AUV for rendezvous and recovery.

Possibly the most important feature of an AUV is its ability to survive a mission and be recovered. It is arguable that in the oceanographic science community the collection of data is secondary to this. This is particularly the case where communications with the AUV are limited, which is most of the time when working in extreme environments, especially under ice. An AUV needs to be robust. Its mechanical construction must be able to withstand knocks both during the mission and during launch and recovery.

2.3 Vehicle Protection

A fundamental aspect of vehicle protection is collision and obstacle avoidance. Much work has been demonstrated in simulation and in controlled test environments, but little has followed through into operational AUVs.

An example of collision avoidance that is particularly relevant to vehicles working in extreme environments is the under-ice collision avoidance of the Autosub AUV, developed and operated by the National Oceanography Centre, Southampton. Using upward, downward and forward ranges to objects determined by narrow beam sonars, in conjunction with depth, the vehicle is able to detect the imminence of high collision risk situations and take basic avoidance measures. The motions of the vehicle are shown in Figure 4.

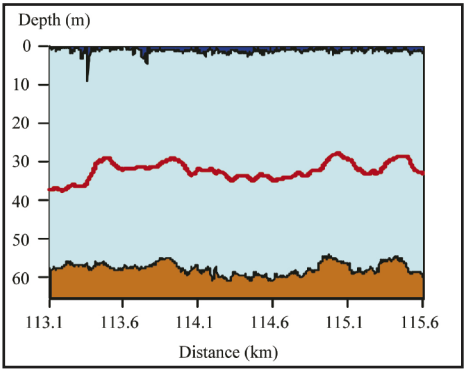
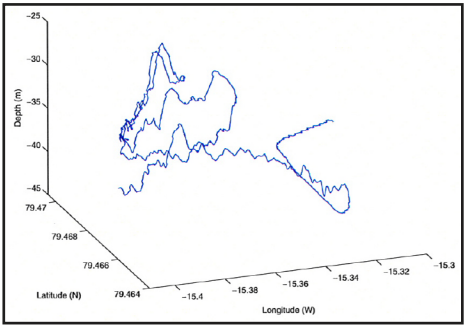


Figure 4: Autosub avoidance (top), avoiding the bottom in the vertical plane, and (bottom) a three-dimensional representation of the collision avoidance path on mission 365



Other vessels pose a major threat when an AUV is approaching the surface, working close to the surface or actually on the surface. This area tends to be addressed in a procedural way with AUVs

in these situations, either being under close supervision of support vessels and/or operating in extremely remote areas. There is considerable scope for the development of autonomy in this aspect of operations.

A key aspect of autonomy is realised in a system's ability to maintain itself with health checks and corrective measures that make use of redundancy in systems. While more common in aerospace technologies, the marine domain of AUVs has not, to date, demonstrated this in operational vehicles. The state of play tends to be one of fault detection and emergency response: a mission is prematurely terminated, or the AUV is put into an abort state with ballast being dropped and the vehicle returning to the surface or taking on ballast and descending to the seabed (Ferguson, this volume). The former option is not available to under-ice operations, however. Extensive research in this field has been reported by Hamilton *et al.* (2001) and Alessandri *et al.* (1999).

2.4 Operational Simplification

The majority of scientific missions require a series of waypoints that range from a simple transect to a grid or lawnmower-type survey. In the case of extreme environment missions, such as under ice, the navigation requirements are currently kept relatively simple. Tools that allow the automatic planning of a mission and, more importantly, simulation and semantic checking of scripts are vital. Typically, the configuration of an AUV's sensors and systems is also an area where automation is necessary in order to reduce human operator error.

Hypothesis or task driven mission specification is perhaps the holy grail of any scientific autonomous vehicle. The ability to specify a mission in terms of a number of topics of scientific interest, and then pressing the 'go' button would provide the scientific user with a very powerful and cost-effective tool. This technology is applicable to all autonomous robotic vehicles, and not only the underwater domain. However, to date such systems are not in operational use.

Outside of the task of mission planning there is much effort required in technical preparation of an AUV. Larger AUVs in particular have a diverse range of sensors and equipment that must be readied for each deployment, as well as batteries that need monitoring, charging or replacing. The key to this operation is communication between technical personnel, with tasks being allocated, executed and checked off in the correct sequence.

Another important aspect of simplifying the operation of AUVs is use of automatic fault detection and isolation. Here, there is considerable overlap with the health and redundancy section above. Providing operators with a vehicle that can self-diagnose its faults is another powerful and cost-effective technology. Related to this, and mentioned in the previous section (2.3) on vehicle protection, is the provision of redundant systems to increase the vehicle's fault tolerance.

3. Operating AUVs in Extreme Environments – Technology Gaps

In extreme environments the single most important outcome is that an AUV does what it is expected to do; the inclusion of autonomy should increase the chances of this.

Expectations may vary depending on the viewpoint of personnel involved. Ultimately, however, the successful conclusion of a mission is the result of an intricate balance of the interactions between all the operational systems, including the support platform and the operating technicians themselves. It follows that there is an inherent risk in increasing the complexity of a system, and this prompted the following questions and discussions that were the output of the Autonomy and Collision Avoidance breakout group from the Masterclass:

- **What is an acceptable level of systems complexity, to what degree is increased autonomy desirable?**

There is a community consensus that autonomy should not be introduced if there is a resulting negative impact on reliability and likelihood of mission completion. The interaction of components in a system that is autonomous is critical and is very hard to test. It is the case that whenever an autonomous vehicle is sent on a new mission to a new region, there will be untested interactions between the systems and the environment. It is the task of the design engineer to make the behaviour of the vehicle robust enough to survive. Added complexity makes the test and performance task more difficult and thus more expensive. As an illustration, it has been stated that the requirements for an AUV should be a 90 percent probability of mission success and a 99.5 percent probability of survival.

- **Has collision and obstacle avoidance been solved?**

It was unanimously agreed that collision and obstacle avoidance has not been solved, with the possible exception of some specific and limited cases. Additionally, it was noted that collision detection has not been observed in an operational AUV. This state of play is evidenced by the limited examples of operational AUVs making use of avoidance behaviours and the simplistic nature of the missions to which that these vehicles are limited. One problem that has been highlighted is that the requirements are continuously changing.

A key aspect of avoidance is that of avoiding surface vessels, with a particular emphasis on the support ship, which is the main culprit in AUV-surface vessel collisions. Technical solutions to this particular problem are seen as very difficult to achieve, and most AUV operators resort to the implementation of risk reducing procedures.

- **What types of autonomous control behaviours would be useful?**

As previously discussed and illustrated, with nested surveys and sensor gradient tracking, there are a small number of autonomous survey behaviours being introduced into operational AUVs. As confidence is gained, more will follow. One area of future development potential is that of adaptive and active sensing. Included here are selective switching of sensors, dynamic optimisation of sensor configuration (for example side-scan sonar) and sample collecting. These behaviours are highly situation specific and are probably not hard to implement. However, their impact on other AUV operations is critical, and the test and validation can be time consuming and expensive.

- **How can autonomous control behaviours be made to be fail-safe?**

Methods are available in systems engineering to cope with failure modes. The problem, though, is one that must be integrated into a vehicle at all levels and during all phases of design. Techniques include the use of redundant systems, voting systems and authority envelopes with supervision taking place on separate computer systems. It was stated that autonomy is a systems approach. It is not intelligence; it is understanding the system well enough to be able solve all the problems.

- **How can autonomy be used to de-skill the operation of AUVs?**

Autonomous mission planning and pre-mission checking, with model data, is seen as a key feature in efforts to de-skill the AUV operation. AUVs operate in a three-dimensional domain and there is an observed tendency for mission planning tools to present missions in two-dimensions only – those of latitude and longitude, with depth and altitude being sidelined. A requirement for tools to process logged data automatically and dynamically for systems performance relative to expectations based on model data is needed to highlight performance trends and to flag poorly performing components. Careful thresholding of information is needed to generate critical warning events without operator desensitisation and the risk of false alarms compromising the successful outcome of a mission.

Acknowledgments

The authors thank the participants at the 2006 Masterclass in AUV Technology for Polar Science held in Southampton for discussion that provided the background for the conclusions of this paper.

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'When Things Go Horribly Wrong'

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Abstract
Autonomous underwater vehicles (AUV) have been in development for over 25 years, and their use as a science tool is becoming commonplace. In the past ten years, a number of operations have been undertaken in ice-covered waters. Their use, however, continues to be infrequent. Generally, the logistics and support of polar AUV operations are more complex, and can be more expensive, than for operations conducted in open water. While the actual operation of the vehicle is little different than in open water, the manner in which the mission is planned can vary substantially to reflect the reality of an ice-covered surface. Finally, there is a perception that the risk of losing a vehicle is higher than in open water. One of the conclusions of this Masterclass in AUV Technology for Polar Science was that a Best Practices Guide be developed to recommend the manner in which under-ice AUV operations could be carried out. The Engineering Committee on Ocean Resources (ECOR) Specialist Panel on Underwater Vehicles* has taken on this task. Given the limited experience with AUVs in the polar environment, it is intended that this document be one that is evolutionary, where contributions and updates from the community are welcomed.

* See http://www.rina.org.uk/underwater_vehicles_specialist_panel.html

1. Introduction

The capabilities of AUVs continue to evolve, and the possibility now exists of these vehicles being capable of making decisions based on their own information about the environment, (Pebody, this volume). However, most of the polar experience with AUVs has been with vehicles that are programmed to carry out pre-planned or supervised missions.

These missions can be either ice- or sea-based. We define an ice-based mission as an AUV mission that originates from a hole in the ice and terminates at the same or another ice hole. A sea-based mission is one that originates and terminates from a ship located near the ice shelf. For completeness, a hybrid mission is an ice-based mission with termination at a ship, or vice-versa.

2. Scope of a Polar Mission

Most AUV missions, including those conducted in polar environments, have two distinct phases: planning and mission execution. Some missions have a third phase that involves locating a lost vehicle and possibly rescuing it, otherwise described as, 'What to do when things go horribly wrong'. Any discussion of things gone horribly wrong must consider the planning and mission execution of under-ice missions, as it is in these phases that the possibility of disaster is bounded.

3. Planning

The planning phase is the activity that precedes the deployment of the AUV. In this phase, the manner in which the AUV will be operated is determined. Aspects that may be included are the mission requirements; integration of new mission or payload sensors; the acquisition of spare parts for the vehicle or payload; logistic and mobilisation planning or how the shipment is going to get to the ice and into the water; mission simulation; issues related to insurance for personnel and the vehicle; and finally, environmental issues.

All of these aspects need to be considered to some degree when planning any underwater vehicle mission. The principle differences with polar operations are that the areas of operation are generally very remote and that some form of ice cover is normally present. The remote nature of the operations makes communications with outside agencies sporadic. Re-supply is generally very costly and time-consuming, and there may be periods where weather precludes any operation.

This environment provides its own challenges to the AUV operator. Generally speaking, it is not a suitable environment for testing new equipment or concepts. Consequently, planning should involve the testing of new equipment or integrations in open-water prior

to a deployment*. There may be instances where the operation of specific equipment in the AUV during a polar operation risks the safety of the AUV. In these instances, if the operation must proceed, consideration should be given to conducting other less risky operations first (Griffiths and Trembanis, this volume).

The condition of the ice surface will be fundamentally important where ice-based missions are concerned. The thickness must be studied from a safety perspective and due to the requirement of making a hole through which the AUV can operate, for some missions. Other holes for remote communications and positioning may also be required, and as these are likely to be smaller, they will require some plan to ensure that they do not freeze over. Air transport, for example a helicopter, may be needed in some circumstances.

Ice cover also alters the environment in which the vehicle operates. Because of the ice cover, a near isothermal water column, yet with the likelihood of a strong shallow halocline (especially in winter), and the absence of sea state and shipping noise, acoustic conditions are likely to be very different to those in open water. The downside of this is that the ice cover is going to create more severe acoustic multi-path in shallow water. These factors need to be considered in planning missions and, if available, acoustic data from prior missions in the area should be referenced. For sea-based operations, the mission will encounter the same conditions under ice; however, at the marginal ice zone, conditions may be significantly worse.

In many cases, environmental regulations are developed specifically for polar regions, and these should be fully understood prior to the commencement of operations. These regulations may include provisions for dealing with polar wildlife. Environmental and weather data may not be as accurate or frequent as it is in other parts of the world. Local knowledge may ultimately be the best source of information.

The conduct of operations in areas of ice cover also dictates that some plans exist in the event that that vehicle is lost or becomes disabled. Such a plan may require the availability of specialised rescue equipment. In the event that the operator wishes to obtain insurance to cover loss of the AUV, the underwriter will look for evidence of a rescue plan (Griffiths *et al.*, 2007). In addition, a fault-tolerant design and a well thought out fault management strategy may reduce the premium.

4. Mission Execution

Mission execution consists of planning the actual mission runs which the AUV will undertake, simulating them, launching the vehicle, conducting these mission runs and

* Testing of equipment and procedures may be feasible in more benign under-ice environments, such as under lake ice or in the ice-covered upper reaches of fjords in accessible areas such as Newfoundland (lakes) or Norway (fjords).

finally recovery. In managing these operations, common sense, good judgement and an appreciation for local knowledge will go a long way to assuring a successful outcome.

Mission planning and simulation has become standard practice for AUV operations. Where a simulation capability is not available; the mission plan is generally checked by an individual not involved with input to the plan. In the case of polar operations, either a simulation or an independent check (or both) helps to ensure that simple programme errors are caught before they impact on operations.

In the same way, a complete review of the fault management plan is often undertaken to ensure that fail-safe actions established for surface operations are appropriate under ice. For instance, in a surface mission, a fail-safe might simply consist of shutting the vehicle down and letting it float to the surface. In a polar operation, it is probably better for the vehicle to attempt to get back to its base, or failing that, to 'park' on the bottom – as happened with *Theseus* (Ferguson, 2003). As is the case with open-water missions, operations are generally not planned in depths exceeding the vehicle's depth rating. In the case of polar operations, the AUV is often fail-safed so that it will sit on the bottom rather than float to the surface. Generally, this makes it easier to locate if it is lost or disabled.

In the conduct of polar operations, operators generally include several short missions at the start to get the feel for the local conditions and to ensure that the vehicle is essentially functional. In some cases, high-risk data collection missions may be scheduled at the end of the operating period, particularly if such missions are not critical to the overall success of the operation.

As the vehicle is launched in polar latitudes, it may quickly go through a large temperature change – possibly from –40 or –50 degrees Celsius in an unheated ice camp in winter, to –2 to 0 degrees Celsius in seawater. Where there is a temperature concern, vehicles can be stored in heated tents or huts.

Ideally, missions can be planned in a manner that reduces or minimises navigational drift, even if this involves some periodic manoeuvre. At some point, however, the drift becomes unacceptable and it is necessary to update the vehicle's position. In planning the vehicle's mission, the location is determined by where the ice is thick enough to support the equipment involved and thin enough to drill holes. Some form of heating system is used to keep the water in the hole from freezing over.

In recovering the vehicle at an ice hole, precise navigation is required at the end of a mission – just when the drift in the vehicle's navigation system may have reached its allowable limit. A number of operators have used an inverted USBL system, in which the receiver is carried in the AUV (McPhail, this volume). This allows very accurate homing to a point at which the ultra-short base line (USBL) beacon is placed.

5. Loss of the AUV

AUVs may sink in water depths exceeding their depth limit. In this case, there is little that can be done, other than to consider a retrieval of the debris if environmental regulations require or if the data justifies the cost of recovery. An AUV can also be known to be lost or it can be missing. If the AUV is known to be stopped on the bottom or under the ice surface, it is probably disabled, thus some form of intervention will be required.

As is the case in open water, AUVs can also become lost for periods of a few minutes up to a very long time. In cases where transits are involved, the vehicle will leave an area where positioning and communications are possible, but may check in at pre-planned points along the route. In this case, any loss will become apparent some time after it has occurred.

In more than a few instances, AUVs that have gone missing have been found exactly where the mission plan took them, and a careful review of the mission plan may unearth a simple mistake. Along the same line, a review of the fault table may provide some clue as to where to look for the vehicle.

As there is some uncertainty about the status of an AUV that has not been heard from at an expected time, it may not be prudent to alert higher authorities or the insuring authority straight away. If the vehicle's location is not known, a search may be organised. If the vehicle is on the bottom, it should be quite easy to track the emergency acoustic beacon when the search party is within range. When the vehicle is located, an attempt is usually made to establish communications through the telemetry link. If this is operational, it should provide a synopsis of the vehicle's condition, as well as reveal what the problem is. From there, it may be possible to 'coax' the vehicle back to the surface, or even resume its mission. If not, it may become necessary to resort to the use of heavier, more sophisticated lift equipment, such as remotely operated vehicles (ROV), and at this point, the economics of a recovery should be re-examined.

In the end, common sense, good judgement and an appreciation for local knowledge may make the difference between a successful recovery and the failure to find the vehicle.

6. Follow-On Action

Several participants in the breakout session expressed the need for a Best Practices Guide for Polar AUV Operations. The Engineering Council on Oceanic Resources (ECOR) has a Specialist Panel on Underwater Vehicles, which has agreed to develop such a publication. The Panel met in September 2006 to consider a first draft and plans to introduce the revised draft of the Best Practices Guide to several websites by mid 2007*.

* See http://www.rina.org.uk/underwater_vehicles_specialist_panel.html

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Towards a Risk Management Process for Autonomous Underwater Vehicles

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Abstract

There is increasing interest from the marine science community in using autonomous underwater vehicles (AUV) under ice shelves and under sea ice. These environments pose challenges to the vehicle and support team, and they mean that recovery may be almost impossible, or very expensive, should the vehicle develop a fault, particularly when beneath ice. This paper reviews recently published work on AUV reliability and develops a risk management process for autonomous underwater vehicles (RMP-AUV) tuned to the needs of the responsible owner working with a technical support team. The RMP-AUV provides a framework for the responsible owner to determine an acceptable risk using mainly objective information, augmented with subjective judgement on the priority of the proposed vehicle campaigns. A process is defined whereby the technical team determines the probability of loss based on the most applicable historic data for the vehicle. If this is less than the risk acceptable to the owner, RMP-AUV then requires this assessment to be verified, for example through a proving campaign. How a campaign can be designed to meet this objective is discussed and other risk mitigation strategies are outlined. Examples are included to illustrate the how the proposed RMP-AUV would work, using actual reliability data from the Autosub AUV. We are some way from having sufficiently reliable (or sufficiently inexpensive) AUVs that the task of risk assessment in polar environments becomes trivial. Until that time, careful performance and risk assessments will be needed. Furthermore, those assessments should be used to drive forward improvements in AUV reliability so that the full potential of autonomous systems to deliver data from the polar regions can be realised.

1. Introduction

On 16 February 2005, at Fimbulisen on the edge of the Antarctic ice cap, an autonomous underwater vehicle (AUV) set out on a science mission under the ice shelf. The vehicle did not return. *Autosub2* was lost, under 200 m of ice, some 17 km from the face of the ice shelf. The exact reason remains unknown. The previous mission had been successful, bringing back startling and unexpected information on the roughness of the underside of the ice shelf (Nicholls *et al.*, 2006). It is quite possible that the cause, or causes, for the loss had nothing to do with the polar environment itself (Strutt, 2006), and yet the environment was a major factor, as it precluded recovery of Autosub. With increasing scientific interest in using AUVs to make observations beneath ice shelves and beneath sea ice, funding agencies are asking whether they can afford the risk of operating expensive vehicles in an environment from which recovery is nearly impossible, or at least very expensive should there be a failure.

What is clear from anecdotes (Stokey *et al.*, 1999) and from the increasing cost of insurance (Griffiths *et al.*, 2006) is that the reliability of AUVs needs to be improved. Unfortunately, there is a severe lack of data and analysis in the open literature on AUV reliability. What there is gives rise to concern. Published results for *Autosub2* (National Oceanography Centre) and Dorado (Monterey Bay Aquarium Research Institute) suggest that for both vehicles the historic probability of completing a 24-hour mission without a fault was below 61 percent (Griffiths *et al.*, 2003a; Podder *et al.*, 2004). Figure 1a shows the reduction in probability of Dorado missions ending successfully as the mission time increases, as well as

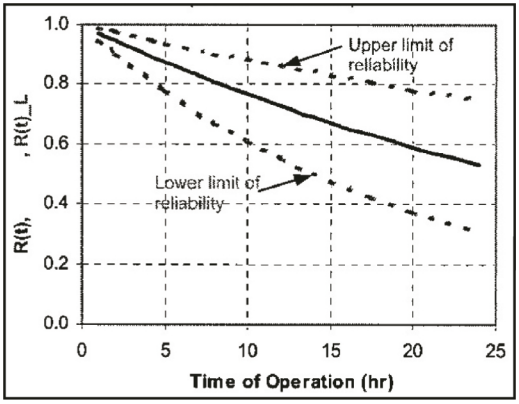


Figure 1a (top): Probability of missions ending successfully (that is, without a fault causing a premature termination) for the Dorado AUV, from Podder et al. *(2003)*

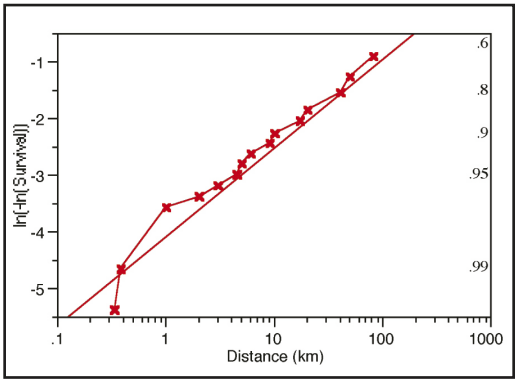


Figure 1b (left): Probability of survival for the Autosub AUV under an ice shelf based on data from 240 missions, estimated using a Weibull distribution with $\alpha = 403.9$ *and* $\beta = 0.678$*. The right hand scale shows probability of survival, from Griffiths* et al. *(2003a)*

the growing uncertainty in the estimated probability of success as mission time increases. For Autosub, Figure 1b shows the probability of survival for under-ice-shelf missions of increasing range based on a Weibull model fitted to the reliability data gathered over 240 missions. It was this analysis that was accepted by the UK Natural Environment Research Council (NERC) indicating that the Autosub Under Ice programme was indeed high risk, but with high gain potential. The analysis was shared with the vehicle's insurers and led to an annual premium quotation of 95 percent of the vehicle's value (with a return of part of the premium for each year the vehicle survived). As this level of premium was unacceptable, NERC took the decision to fund the construction of a second Autosub (now *Autosub3*) as insurance for the research programme.

However, there are signs that AUV reliability is improving. Since the Podder *et al.* (2004) paper, Monterey Bay Aquarium Research Institute (MBARI) has used a new vehicle, *AUVCTD*, bimonthly on a 100 km transect in Monterey Bay. The reliability has increased over time, due to the engineering team's ability to find and then correct faults, followed by use at sea on such a regular basis (Thomas, 2006). AUVs such as Autosub that have been used on an expeditionary basis have not had the benefit of such regular use, static configuration and from one location to help drive down fault occurrence. A polar equivalent to the *AUVCTD* programme is not infeasible; for example, a programme sea ice studies using an AUV from a shore base – perhaps from an underwater garage. However, it is likely that the sponsors of such a programme would need to accept higher risk during the initial period while the reliability improvement was being achieved.

Regular use with a set, or slowly evolving, vehicle configuration has also been a major factor in improving the reliability of AUVs used by industry. Experience with the *C-Surveyor* AUV showed that as delivered from the manufacturer the availability was low, but that extensive use over 12 months and more improved the availability in any one month to over 90 percent (Figure 2; Chance, 2003). In this figure, 'availability' is not explicitly defined, but using the accepted definition of:

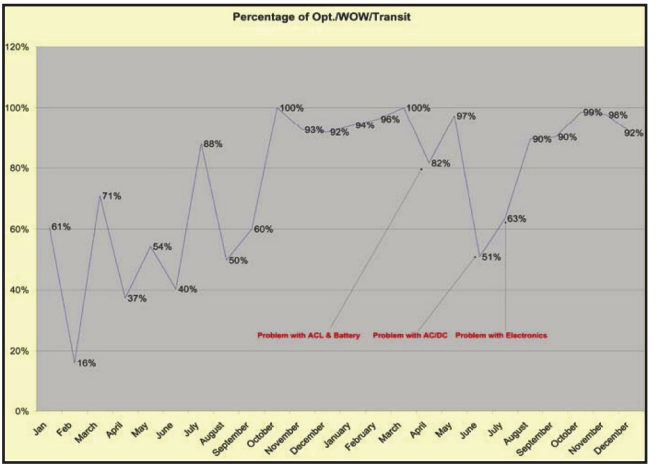


Figure 2: Availability for C&C Technologies AUV over two years and 24 000 km in offshore industry. Delivered, availability was ~20 percent, but grew to 90–100 percent over year-long operations (Chance, 2003)

[(Mean Time between Failures)/(Mean Time between Failures + Mean Down Time)] x 100%

shows that availability and reliability, although related, can be decoupled to a certain degree. That is, a high availability can result from a system with regular failures if the mean down time from those failures is much smaller than the failure interval. Conversely, availability can be low if a simple failure results in an extended down time due to lack of spares or consequential damage – e.g. a minor in-water failure leading to premature recovery, during which the vehicle sustains severe damage completely unrelated to the initial failure.

As modifications were made to the *C-Surveyor* vehicle, the availability dropped, as shown by the downward excursions in Figure 2. This effect of modifications and upgrades leading to a temporary reduction in reliability has also been shown for *Autosub2* (Griffiths et al, 2003b).

It is against this background that we consider it timely to move towards a proactive and systematic risk management process for autonomous underwater vehicles (RMP-AUV). The basic elements of a risk management paradigm that could be adapted for use with AUVs have been set out by Strutt (2006) in the report of the Autosub Loss Inquiry Board. In this paper, we develop the basic risk management paradigm into a process tuned to the AUV application, recognising the elements and the uncertainties involved when dealing with autonomous systems.

The key steps in developing the RMP-AUV are:

- The design of a risk acceptance process, including the issues over identifying who might be the responsible owner of the risk and who might comprise the technical team.
- Defining a method by which the responsible owner might determine the acceptable risk for any particular mission or campaign[1]
- How the technical team could perform fault assessment and subsequently calculate the probability of the vehicle surviving the missions or campaign, including assessing the trials time needed to obtain confidence in the fault statistics
- A risk evaluation stage within the risk acceptance process that tensions the risk acceptance of the responsible owner against the expected probability of survival, calculated by the technical team
- Risk mitigation strategies, to include procedural measures, technical, demonstrated quality assurance, and use of tools such as fault tree analysis (FTA) and fault modes effects and criticality analysis (FMECA).

2. The Basis of a Risk Management Process for an AUV

2.1 A Risk Acceptance Process

The basic risk acceptance process of an RMP-AUV is shown diagrammatically in Figure 3. This has been built from the basic paradigm for risk management outlined in Strutt

[1] We define a campaign as a series of individual missions sharing a common theme or location or deployment vessel.

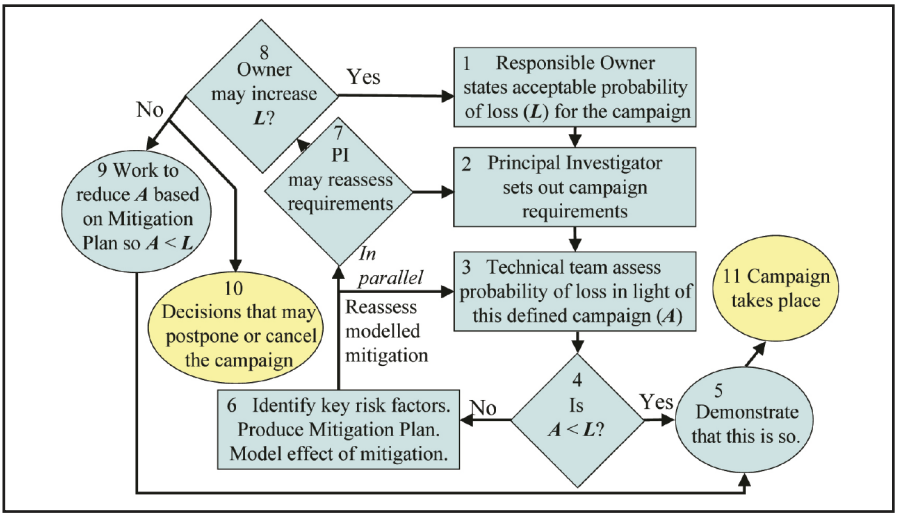


Figure 3: A flow chart of the risk acceptance process within the RMP-AUV

(2006). The process begins with step 1, where the responsible owner states an acceptable degree of risk. This degree of risk might be expressed as an acceptable probability of loss, an acceptable insurance premium or an acceptable financial risk over any particular campaign.

In practice, different presentations of risk acceptance are unlikely to be independent; indeed they are likely to be strongly linked. For example, the insurance premium is likely to be strongly influenced by the probability of loss if, as should be the case, all factors are declared to the insurance brokers and underwriters (Edwards, 2000; Griffiths *et al.*, 2006). The annual premium is unlikely to be lower than $L * C$ where L is the probability of loss in any one year and C the capital cost of the AUV. In the process developed here, we assume that the responsible owner will declare the risk acceptance as a probability of loss over a campaign. In section 2.3 we explain how the owner might arrive at an acceptable probability of loss.

In step 2 the campaign and mission requirements are set out by the commissioner of the work (e.g. the principal investigator of a science project). The requirements must include sufficient detail for the technical team to be able to assess the risk. The factors that might affect risk include (among others):

- The environment in which the missions and campaign will take place, e.g. in open water; in water depth exceeding the pressure rating of the vehicle; under sea ice; under shelf ice; close to the seabed; in gentle or in rough terrain; and at what height, the likely sea and weather conditions at launch and recovery
- The number, type and duration or track lengths of the individual missions that are needed to deliver the campaign objectives

- The mode of operation, e.g. under escort and in continual communication or unattended
- Whether the campaign uses robust, well-proven instrumentation or whether novel or untried instruments or systems are included, including instruments that take in water
- The complexity of the mission programming requirements
- Whether, and to what degree, the ship, the officers and crew have experience with AUVs.

Risk factors for AUV operations are discussed in more detail in Griffiths, Millard and Rogers (2003).

In step 3 the technical team takes the information on campaign requirements and arrives at an estimate of the probability of loss, *A*, using the procedure described in Section 2.4. Step 4 involves comparing the acceptable probability of loss, *L*, of the owner with the estimated probability of loss, *A*, calculated by the team. If *A* is less than *L* then the indications are that the risk of loss during a campaign, as defined by the requirements, is acceptable. In this case the next step (step 5) would be for the technical team to demonstrate that its assessment of the risk was realistic. This could be, for example, by mounting a reliability trials cruise and demonstrating that during the trials the vehicle reliability statistics were no worse than those used to assess the likelihood of loss in step 3. If the statistics during the trials cruise were worse, then step 3 should be repeated with the updated through-life statistics and the comparison step 4 repeated. If not, then the campaign would take place (step 11).

If the comparison at step 4 shows that *A* is greater than *L*, the indications are that the probability of loss would be unacceptable to the owner. Should this be the case, we propose that step 6 should require the technical team to identify the key risk factors and produce a written mitigation plan, with a budget and timetable. The effects of the proposed mitigation measures on the probability of loss would be modelled in a way that would take into account the reliability history of the vehicle. In light of the outcome of the initial analysis of step 4, and the likely effect of mitigation from the modelling exercise, in step 7, the client (principal investigator) may review the campaign requirements to reduce the risk. This could be, for example, by reducing the track lengths or the number of missions with the highest risk. Steps 3 and 4 would then be repeated with the new requirements. There may well be tension between the client, perhaps unwilling to reduce the campaign requirements for valid scientific reasons, and the owner, who may require review. Furthermore, it is possible (certainly in the case of a funding agency such as NERC) that the client may be funded through a grant from the same organisation that is, in effect, the owner of the AUV. Additional and/or more complex tensions may exist in cases where the client and the responsible owner fall under different organisations or funding sources.

If the measures considered so far (risk mitigation and revised campaign requirements) do not lead to an acceptable mission risk, in step 8 the owner would be asked whether

he would be willing to increase the probability of loss that he would accept. If this is not possible, and it may well depend on the increase in risk being demanded, the outcome would either be (a) a decision to postpone or cancel the campaign (step 10), or (b) if there was an expectation that the measures in the mitigation plan would reduce ***A*** so that $A < L$, work would take place according to the mitigation plan (step 9). This would inevitably involve expenditure and would require further sea trials to demonstrate an increase in reliability (step 5), and if successful, would be followed by the science campaign (step 11).

It is possible to assess the cost benefit of the expenditure, E, to improve reliability against the cost of increasing the owner's acceptable probability of loss (upward from L). If $E < (A - L) * C$ then there is an immediate net benefit to improving the vehicle's reliability. If not, the indication is that the cost of improving the reliability of the vehicle would need to be amortised over more than one campaign.

2.2 Who Might Be the Responsible Owner?

For a commercial operator of an AUV, the answer to the question of who is the responsible owner with regard to risk management may be straightforward – for example, it may be the chief financial officer. In a research environment, the answer may be rather more complex. It may depend on whether the AUV has been purchased as an asset on a grant to an individual or consortium and operated by the individual or consortium for their own purposes, or whether the AUV is an asset in an equipment pool, funded for the benefit of a broader community. In the former, the consequences of risk and loss are contained within a group or consortium; in the latter, the consequences may be more far-reaching.

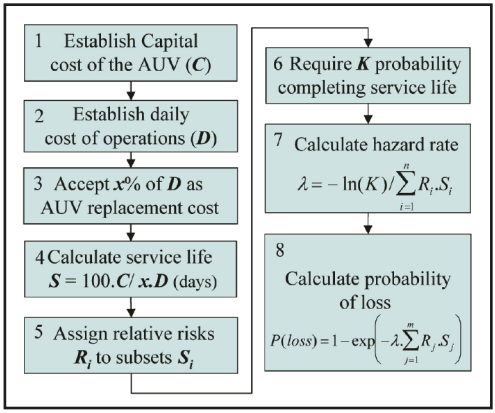
In the case of an individual or consortium operating an AUV purchased with a grant, and the legal ownership of the vehicle resting with an institution (rather than the grant-awarding body), the responsible owner is likely to be the principal investigator, perhaps with oversight from the head of department. Where the vehicle is part of a facility – whether the vehicle is owned by the facility operator or by the body that funded the vehicle – it would be appropriate for the director in charge of the facility to be the responsible owner. However, where the risk of loss is small in the envisaged campaign, the director may delegate the responsibility, e.g. to the head of the facility or the operating group. 'Small' may be defined as the level of risk that would be insurable (in current markets, below 15–20 percent), even if insurance was not purchased. The indications are that underwriters are now unlikely to accept AUV risks that would require annual premiums above 15 to 20 percent of the vehicle's replacement cost (Griffiths *et al.*, 2006).

2.3 A Process for the Owner When Deciding on an Acceptable Risk

We propose a process for the owner to use when deciding on an acceptable risk that is informed by the major costs of owning and operating an AUV. The process is shown diagrammatically in Figure 4.

Step 1 identifies the capital cost of the vehicle (*C*). This may be its build or purchase cost or the cost to replace. In step 2, the typical daily cost of operation (*D*) is estimated based on the type of campagn proposed, the AUV technical support requirements, the cost of capital for the vehicle and part of the charter rate for the class of vessel and the cost of the onboard science team. This recognises that the vessel and science team may spend time on non-AUV activity. These two steps are purely objective. Others involve subjective judgement on the part of the responsible owner.

Figure 4: A flow chart for the owner when determining an acceptable risk for a particular campaign



Step 3 requires the responsible owner to state what fraction (*x* %) of the daily rate, *D*, he is willing to accept as a loss replacement charge for each day of AUV operation throughout its service life. This may be a real or a notional charge, and is likely to be informed by the policies and practices of the organisations involved. There is unlikely to be a single figure that will suit all scenarios. In the case of an individual or consortium operating an AUV, considerations might include, among other factors, the quality and novelty of the science proposed, its timeliness, the international context, the vehicle's prior and future programme and the importance of the proposed research to the individual or consortium. However, for an AUV operated as a facility, it would not be appropriate for facility staff to make judgements on these factors, in which case a fixed loss replacement charge would be fair.

Irrespective of how *x* is determined, the required service life in days can then be calculated in step 4 as: S = *100.C / x.D.* Implicit in this calculation is that the same loss replacement charge is attributable to all of the users, irrespective of the risk profile of their particular campaigns.

Step 5 recognises that the vehicle will undertake campaigns with varying risks throughout its service life. The service life is split into *n* user determined subsets. Each subset, *i*, of S_i days, has a relative risk assessment of R_i, where *R* for the lowest risk open-water missions is subjectively taken as 1. Assessing relative risk depends greatly on eliciting opinion on risk from experts – a subject in itself (e.g. O'Hagan *et al.*, 2006).

In step 6 the owner declares the minimum acceptable probability (*K*) that the vehicle will survive to the end of its service life[2], from which the hazard rate (λ) can be

[2] Clearly *K* (probability of completing service life) must be less than (1 – *L*) the probability of surviving the campaign being considered.

calculated (step 7):

$$\lambda = -\ln(K) / \sum_{i=1}^{n} R_i . S_i$$

assuming a constant baseline hazard rate for the lowest risk open-water missions throughout the vehicle's life.

The acceptable probability of loss for a proposed campaign of y days with m subsets of activities S_j, each with a risk factor R_j is calculated in step 8, where:

$$y = \sum^{m} S_j \quad \text{then:}$$

$$P(loss) = 1 - \exp\left(-\lambda . \sum_{j=1}^{m} R_j . S_j \right)$$

A worked example for the Autosub AUV is shown in Figure 5. Typical information that is required to set up the problem is shown. Three different risk scenarios are included – open water, under sea-ice and under shelf-ice – that will be encountered during the vehicle's service life. These are used to calculate the through-life hazard rate. For the particular campaign whose risk acceptance needs to be calculated, these scenarios (or others) may be used. The relative risks need to be kept under review as new information is gleaned from the operation of Autosub and other AUVs under different conditions. For this exercise, we suggest that the risk factor for operation under sea-ice is taken as 3, and 10 for under shelf-ice, reflecting the far lower probability of recovery from malfunction under an ice shelf.

At this stage of development of the RMP-AUV, these risk factors have a high degree of uncertainty and subjectivity. In polar regions (the focus of this chapter) the risk factors are most clearly differentiated in recovery potential, yet in other missions and settings the critical risk factors may exist in other operational domains. For example, in shallow shelf and harbour settings, it is not so much a matter of recovery difficulties but risks associated with collisions or theft, or in military campaigns it may be loss from attack. Actually biological attacks – namely killer whales and leopard seals – may be a real risk factor in polar settings. It was the case for Fetch1 off the Antarctic Peninsula.

The example in Figure 5 is for an under-ice campaign that begins with open-water trials for 10 percent of the 17 days of operation, followed by a mix of under sea-ice (30 percent) and under shelf ice (60 percent) missions. In this example, accepting a 20 percent probability of loss would be the outcome of the decisions made by the owner in completing the input cells.

The spreadsheet calculator[3] can be used to assess the impact of changing risk acceptance criteria on the acceptable probability of loss. For example, should the owner change the 'required probability of reaching end of life' from 10 percent (in this example) to 50 percent,

[3] The spreadsheet is available at http://www.noc.soton.ac.uk/OED/gxg/AUVrisk.xls

then the acceptable probability of loss during this campaign would reduce to 6 percent. If the 'risk premium' in step 3 was to be increased to 50 percent (from 33 percent) of daily operations (and the probability of reaching end of life remaining at 10 percent) then the owner could accept a 28 percent probability of loss for this example campaign.

This process could be applied to analyses where loss does not necessarily mean complete loss of the vehicle, but rather failure to complete mission requirements. Risk assessment and risk management can be applied to the planning of science missions, for which the more likely loss outcome is failure to obtain the mission objectives – giving a more universal applicability to this work.

Worksheet to assist AUV responsible owner in determining acceptable risk

User input in blue cells only. Calculated parameters are in buff cells.

Owner Initial Inputs		
AUV Capital Cost	1250000	GBP
Replacement cost charge	33.3	% of daily operations cost
Required probability of reaching end of life	10	%
Cost of Daily operations		
Direct AUV charge	4000	GBP per day
Fraction science team	1000	GBP per day
Fraction of ship	3700	GBP per day
Total	8700	

Risk subsets	**% service life**	**Relative risk**
Open water	60	1
Under sea ice	25	3
Under shelf ice	15	10
Š		
Š		

Calculated parameters		
Required service life	431	operational days
Replacement cost charge	2897	GBP per day
Hazard rate (λ)	0.001873	per day
Campaign details		
Number of service days	17	days

Risk subsets	**% campaign**	**Relative risk**
Open water	10	1
Under sea ice	30	3
Under shelf ice	60	10
Š		
Š		

Accepable **probability of loss for the campaign**	**20**	**%**

G Griffiths 9 May 2006

Figure 5: Worked risk acceptance example using Autosub data

2.4 A Process for the Technical Team to Assess Probability of Loss

In step 3 of the risk acceptance process, the technical team is required to take the information on campaign requirements and arrive at an estimate of the probability of loss, (*A*). Underpinning the capability of the technical team to make this estimate is its prior experience and track record with the AUV. This can be done using the method described in Griffiths *et al.* (2003a). To summarise, the first requirement is to have a fault reporting and impact assessment process, such as outlined in the flow chart in Figure 6. Engineering actions to correct faults will help make the vehicle more robust. However, the fault history, particularly those high impact faults when underway, can be used to help predict the likelihood of vehicle loss. High impact faults are defined as those that could directly lead to vehicle loss. Examples include: severe collision with topography; leak(s) within large pressure vessels; the vehicle exceeding its design depth; complete loss of power or network transmission; or leaks, short or open circuits in critical power or data connectors[4]. Should such problems happen under ice, for example, the vehicle could be irretrievably lost. In other words, the locale of operations makes what would be less than high impact faults in open water critical faults within the operating locale. This is an area where the eliciting expert judgement is important in setting the risk factors.

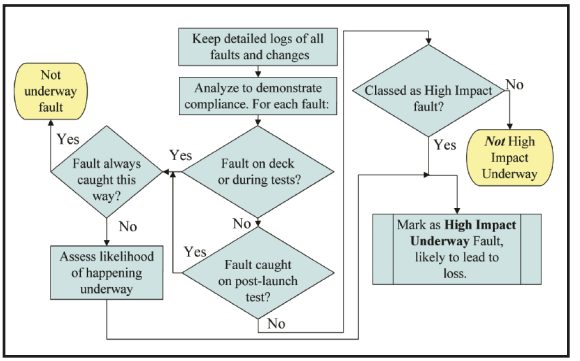


Figure 6: A flow chart for the fault assessment process to be undertaken by the technical team

The mission phases considered in the RMP-AUV have been restricted to those described by different operating locales – open water, sea ice and shelf ice, but this is an over-simplification. In reality, there are a multitude of mission phases independent of locale, e.g. launch, recovery, where increased risk could and should be modelled. Transition between phases, e.g. from surface to dive may also hold separate risk factors. While we recognise these circumstances, with our present state of understanding and our limited data, there would be too much conjecture or subjectivity in assessing each risk.

It is prudent to perform pre-deployment checks on an AUV. Ideally, tests on deck would be followed by in-water tests immediately prior to committing to a mission. Faults caught during such tests would not normally be classed as underway faults. However, if they were high impact faults, there is a need to assess the probability that the fault would or could have occurred when underway. That is, the probability that the fault would not

[4] For further examples, a list of possible technical and root-causes of the *Autosub2* loss is given in Strutt (2006).

have been caught pre-committal to mission is estimated. (Note: this has yet to be built into the process.)

Figure 7 shows the steps in calculating the probability of loss with example data from historic Autosub records. The output of the fault assessment is a table of mission number, the mission track distance (km) and a flag as to whether or not the mission suffered a high impact fault underway. The table forms the input data set for an analysis that fits a Weibull distribution, using, for example, a maximum likelihood method as in SAS Institute's JMP data analysis package[5]. The Weibull model parameters are then used to predict the probability of survival for the mission ranges envisaged in the planned campaign.

Each of the missions should be given a relative risk, as discussed earlier, and this modifies the α Weibull parameter to reflect the risk for each mission. The overall probability of surviving the campaign of several missions is the product of the probability of surviving each mission. In this particular example, the probability of losing the vehicle, at 67 percent, is far higher than the owner's acceptable risk. The vehicle reliability must (a) be improved greatly and (b) demonstrate that reliability growth has been achieved before the owner would contemplate the polar campaign envisaged in this example, or the owner must be convinced to amend the acceptable risk level. This example has illustrated steps 1 through 7 (except 5) in the risk acceptance process of Figure 3.

Step 5 requires demonstrating that the vehicle can achieve the required reliability, and step 9 requires the reliability to be improved. These can be treated together, and section 3 shows how the information gained through trials and targeted reliability improvement can be used to inform both steps.

3. Robustness and Risk Mitigation

3.1 Demonstrating that the Required Reliability Can Be Achieved – Ashore

The Strutt (2006) report recommended additional risk identification and mitigation measures that could be applied to AUV development ashore. These included *a priori* use of tools such as FTA, FMECA and root cause analysis (RCA). Of these, FTA has begun to be used within Autosub (notably at the design stage of the pressure-compensated battery modules for *Autosub6000*). However, broader use of these techniques will require additional resources. These resources have been requested in the NERC Marine Centres' Oceans 2025 programme proposal of March 2006.

3.2 Demonstrating that the Required Reliability Can Be Achieved – at Sea Trials

The risk acceptance process requires that the technical team demonstrate that the reliability needed to ensure that the responsible owner's level of risk is not exceeded. Historical fault data will have informed the process as described in Figure 7, however, results from trials at sea should be used to validate that the vehicle reliability is indeed no worse than expected. The sea trials should be designed to validate the vehicle in conditions as close to the planned campaign as can be achieved. Key conditions should

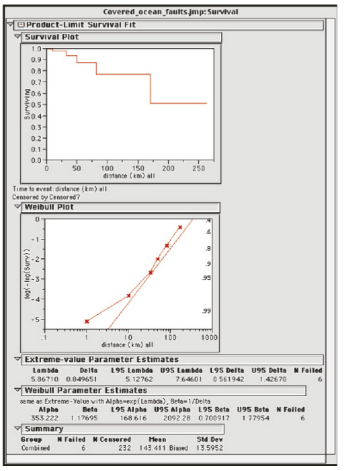
[5] See http://www.jmp.com

Figure 7: Worked example risk calculation using Autosub vehicle data historical for a short under-ice campaign of three ice shelf and two sea ice missions

1. Tabulate the mission data, range and whether high impact fault occurred underway that could lead to loss in under-ice missions.

Mission	km	HI fault?
1	10	N
2	30	N
…	…	N or Y
n-1	40	Y
n	80	N

2. Use a analysis program (for example SAS Institute's JMP® package) to fit a Weibull distribution to the data, where x is the distance variable, α the characteristic life and β the shape parameter. As a precursor, a Kaplan Meier staircase estimator of survival may be derived. Below, from a JMP analysis of 118 Autosub missions, the upper plot is the Kaplan Meier estimate, and the lower, a Weibull parametric fit.



3. From the weibull fit, the parameters α and β and their upper and lower 95% confidence limits can be determined, as in this table from Autosub, where out of 118 missions. Nine failed with high impact underway faults and 109 did not. Note that even with this sample set of over 100 missions, the confidence limits on α and β are large.

α	β	L95 α	U95 α	L95 β	U95 β	N Fail	Censored
483	0.78	173	5105	0.46	1.16	9	109

$$R(x) = \exp\left(-\left(\frac{R_i.x}{R_{shelf}\alpha}\right)^{\beta}\right)$$

In the table below five under-ice missions are listed, which might take place over 15 days, and against each mission range is the calculated probability of the mission ending successfully. For this five-mission campaign, with two missions under sea ice and three missions under shelf ice, the overall probability of returning with the vehicle is 0.33. That is, there is a ~67% probability of loss.

Mission	R_i	km	$R(x)$
201	1	77	0.961
202	3	100	0.892
203	3	130	0.869
204	10	60	0.822
205	10	70	0.801
206	10	110	0.730
207	10	110	0.730
208	10	110	0.730
		767	**0.190**

5. A 67% probability of loss is greater than the owner's acceptable probability of loss of 20%. As this example campaign has little or no scope for reducing the mission ranges, the reliability must (a) be greatly improved and (b) it must be demostrated that reliability growth has been acheived before the owner would contemplate the polar campaign envisaged in this table.

include (among others) depth, duration, collision avoidance parallels, terrain following patterns and sensor payload.

Unfortunately, trials are apt to be short and the statistical uncertainty for the Weibull distribution parameters α and β will, as a consequence of few missions, be large. Nevertheless, we do consider the sea trials approach a valid demonstration of system performance under near-actual conditions.

Figure 8: Example of how trials outcomes may influence the expected probability of survival

Worksheet to assist AUV technical team in determining loss probability

User input in blue cells only. Calculated parameters are in buff cells, model in green.

Trials mission (km)	α / β for single failure for this mission, others successful
5	Š
36	1277 / 0.72
72	582 / 1.16
144	315 / 2.63
200	260 / 6.1
250	Š

Shelf Ice relative risk		10
Team initial inputs	36 km mission fails	200 km mission fails
α	7113	260
β	0.622	6.1

Campaign missions Identifier	Relative risk	length (km)	Probability of survival (%) given 36 km trials mission failed
201	1	77	0.9858
202	3	100	0.9672
203	3	130	0.9615
204	10	60	0.9500
205	10	70	0.9451
206	10	110	0.9280
207	10	110	0.9280
208	10	110	0.9280
Total		**767**	**0.6577**

Campaign missions Identifier	Relative risk	length (km)	Probability of survival (%) given 200 km trials mission failed
201	1	77	1.0000
202	3	100	1.0000
203	3	130	1.0000
204	10	60	0.9999
205	10	70	0.9997
206	10	110	0.9948
207	10	110	0.9948
208	10	110	0.9948
Total		**767**	**0.9839**

Survival analysis packages such as JMP can be used to help set out requirements and analyse trials results. For example, in Figure 8 a hypothetical trials campaign took place with six missions, of lengths 5, 36, 72, 144, 200 and 250 km (707 km in total, or ~110 hours of vehicle run-time). On these trials we posit that one high-impact underway fault occurred, and we examine the impact of which mission the fault happened on the Weibull α and β parameters[6], which in turn determine the estimate of surviving the proposed campaign set out in Figure 5. If the fault happens on the short 36 km mission, the predicted probability of survival for the Figure 5 campaign is 65.8 percent, which exceeds the responsible owner's allowed risk. If, however, the fault occurred on the 200 km mission, the probability of surviving the proposed campaign increases to 98.4 percent, comfortably within the owner's allowed risk.

The implication is that the modelled probability of survival is severely affected by a high-impact underway fault on short trials missions ('short' can be defined either in spatial or temporal terms, there being a general equivalence between the two related to average speed). This result reinforces the importance of tracking down, finding the cause, finding a solution and proving the solution works when such a fault arises. Proving the solution works may well require a further sea trial. It is therefore most important that

[6] Note that the JMP analysis cannot handle a fault on either the shortest (5 km) or longest (250 km) missions.

the vehicle is thoroughly prepared before a sea trial and is in as near-operational condition as possible. Faults that could have been identified in the workshop or in a test tank should have been found and corrected. In assessing reliability, sea trials should be used to run the vehicle on long missions that simulate as closely as possible likely mission conditions.

4. Conclusions

In this paper we have proposed and described, with worked examples, a risk management process for AUVs. RMP-AUV requires close cooperation and a high degree of trust between the responsible owner and the vehicle's technical team. We propose that it is the duty of the responsible owner to set out the risk that he will accept for proposed campaigns. It is the duty of the technical team to estimate the risk of undertaking the campaign using historical information. If the estimate shows that the risk of the proposed campaign is acceptable to the owner, it is up to the technical team to demonstrate that it is indeed so, for example through sea trials. It is for the responsible owner to ensure that adequate resources are available to the technical team to verify the risk assessment, for example by funding trials.

From the worked examples in this paper, it is clear that the historical reliability of research AUVs has been low. This needs to be addressed as a matter or urgency if the technology is to continue to receive support by research agencies. The experience in industry (C&C Technologies with HUGIN) and in research (MBARI with Dorado) is that persistence, consistence and extensive use at sea is needed to grow reliability. A two-week trial cruise is no substitute for the months at sea dedicated to improving reliability (Figure 2 – C&C Technologies) or for the bimonthly missions run by *AUVCTD* (Thomas, 2006).

How might this be tackled for Autosub and UK AUVs? The C&C Technologies route to reliability growth requires extensive periods at sea with a vessel in attendance in deep water. It would be enormously costly. The MBARI route uses a small vessel for near shore deployment, and the vehicle quickly reaches the deep waters of the Monterey Canyon, California. The UK is not well placed geographically to take the MBARI route – our continental shelf is too extensive. However, we do not think that this is a UK-only problem. Neither is it a problem limited to propeller-driven AUVs. Recent NOCS experience with commercial deep-water gliders shows that this emerging technology is also prone to faults underway. It may be appropriate to explore, perhaps on a European basis, the establishment of a test facility for AUVs. The facility would need to have ready access to deep water (over 1000 m) as at MBARI, with facilities for launch and recovery, space for support facilities such as a workshop and sufficient infrastructure to support unplanned recovery when things do go wrong.

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Future Autonomous Underwater Vehicle Campaigns and Missions

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Abstract

Autonomous underwater vehicles (AUV) were first used in the ice-covered seas in the early 1970s, but since that time their usage has been sporadic. More recently the importance of the polar seas in the global climate has come to the fore and the use of AUVs is now routinely discussed by scientists proposing scientific programmes in the ice-covered seas. Even so, only a handful of polar missions have been completed, and hence the long-term viability of a polar AUV programme is not guaranteed. This chapter provides support for the usage of AUVs in the polar seas and suggests options and routes to bridge the perceived gap between scientists' needs and funding agencies concerns. The hope is that it will improve the number of AUV missions in the polar seas over the next decade.

1. Introduction

The polar regions are one of the most inhospitable environments on the earth's surface. Within this region, it is the ice-covered waters that are the most extreme. As a result, the polar oceans, in comparison to all other oceans, remains very poorly sampled, both spatially and temporally. It is only now that the scientific community is beginning to understand the important role the polar regions play in regulating the climate of the world (ACIA, 2004 and references within).

Research in polar oceanography stems from the pioneering work of William Scoresby Jr. with his book, *An Account of Arctic Regions*, first published in 1820 (1969, for an accessible reprint), which has been described as 'the foundation stone of Arctic science'. However, it was not until the launch of satellite radar remote sensing in the late 1970s that the polar oceans could be monitored on a regular and global basis. This results from the fact that radar sensors are not affected by cloud cover or light conditions. Daily maps of the sea ice state (e.g. ice extent, concentration and dynamics) are now regularly generated from space-borne sensors. These sensors generally have a wide coverage but a coarse spatial resolution, in contrast to active radars – such as synthetic aperture radar (SAR) – which offer a better spatial resolution but acquire the data over smaller swath widths and thus have less frequent repeat coverage.

Despite advances in obtaining information on the ice state from satellite-mounted sensors, it is still not possible to measure directly the thickness of sea ice. Essentially, sea ice remains opaque to all satellite mounted sensors, as does the oceanic properties below the ice cover. Therefore, information on under-ice morphology, as well as the ocean below, relies completely on *in situ* measurements. These measurements are usually in the form of spot measurements performed in the summer months from either ice camps or icebreakers.

However, both the location of an ice camp and the cruise track of an icebreaker are dependent on the ice conditions at the time, and the scientific mission objectives may not always be achievable if the ice conditions are particularly heavy. Submersibles, on the other hand, are immune to the ice conditions and are free to travel through the usually benign water conditions present under a covering of sea ice. As such, they can obtain continuous oceanographic and ice morphology (sonar) measurements as they travel in any direction under sea ice.

The advent of nuclear-powered submarines in the mid-1950s revolutionised under-ice operations. They eliminated the need to surface for extended periods of time; a problem that blighted the former diesel powered class of submarines. In the International Geophysical Year the nuclear powered submarine USS *Nautilus* conducted the first under-ice transit of the Arctic Ocean, being the first vessel to reach the North Pole on 3 August 1958 (Anderson, 1959).

Since this pioneering mission a significant number of under-ice missions have been performed by the UK Royal Navy and the US Navy submarine fleets, from which the sonar and navigational data have been stored, declassified and released to the scientific community. It was the analysis of ice draft data from submarines that first alerted the world that the summer sea ice within the Arctic was thinning at the astonishing rate of around 40 percent since the 1970s (Rothrock *et al.*, 1999; Wadhams and Davis, 2000; Rothrock *et al.*, 2003). This amounted to a reduction in mean thickness of 1–1.3 m with an accompanying reduction of some 73 percent in the frequency of deep pressure ridges (Wadhams and Davis, 2001). In more recent years, military expeditions have been carrying oceanographic packages to supplement the growing ice thickness dataset collected in this region.

Despite it being almost 50 years since the first transect across the Arctic by submarine, the latter's observations remain unique, as they are the only direct, simultaneous measurement of underside topography and oceanographic properties available to us on a synoptic scale. As such, they are the only benchmark we have at present to identify secular changes in the polar oceans, e.g. ice thickness and associated morphological parameters such as ridge spacing and depth.

There are however many regions within the polar seas to which submarines are unable to venture. For example, in the Antarctic military submarines operations are prohibited by the Antarctic Treaty. Due to these restrictions, only patchy information on ice thickness distribution is available for the Antarctic. In addition any ship-based sampling is potentially biased when compared to the true thickness distribution of the Antarctic sea ice cover, because ships tend to steam through thinner regions of the ice cover in order to avoid being beset. Due to this, there is no systematic spatially distributed data available on the total, or regional, Antarctic ice thickness distribution. For this reason the total volume of sea ice forming, and its variability, is unknown and as a result there are no benchmarks to test or improve the accuracy of ice thickness in global circulation models.

Submarines also have an obligation to avoid the territorial waters of sovereign states. In the case of the US and UK, this rules out much of the continental shelf region of the Arctic Ocean, as well as the seasonally ice-covered sub-Arctic seas – the Baltic Sea, the Sea of Okhotsk, the Labrador Sea and the continental shelf around Greenland. Many of these regions are also experiencing accelerated change and there is need to start systematically monitoring the ice and oceanographic conditions within the seasonal ice covered sub-polar seas. This would create a baseline in our understanding of these areas.

Since the end of the Cold War, the deployment of both UK and US submarines in the Arctic has become more sporadic. There are a number of factors which indicate that a replacement vehicle should be pursued vigorously by the scientific community

including: (1) fundamental changes are now occurring in the polar oceans; (2) the availability of submarine operations are predicted to decline; and (3) the timing and location of submarine missions are governed by military rather than scientific needs.

The logical choice is the autonomous underwater vehicle (AUV), as it has many advantages, notably the possibility of performing closely controlled tight or overlapping grids of imaging tracks, as well as high-resolution data collection by being able to travel close to the ice bottom. This is a possibility that manned submarines cannot enjoy for safety reasons. More importantly, AUVs give scientists the flexibility to control how temporal and spatial aspects of the executed missions should be performed. As a result scientists and engineers can react quickly to new scientific discoveries in a way that manned submarines are unable. For these reasons AUVs are the tool of choice for under-ice operations, and they will play a substantial role in obtaining data in critical regions of the world's oceans, which up until to this point have remained inaccessible.

2. AUVs in Ice-Covered Seas

Only recently have AUVs have been used in the polar seas, although a deployment in the Beaufort Sea by a University of Washington vehicle in 1972 was decades ahead of its time (Francois, 1977). Recent missions include both military operations (e.g. laying of fibre-optic cables in the Lincoln Sea, Hopkin, this volume), as well as scientific curiosity. Examples of the latter include making biomass estimates under Antarctic sea ice (Brierley *et al.*, 2002), or imaging the underside of sea ice during operations off East Greenland (Wadhams *et al.*, 2006), and missions under a floating ice shelf in the Antarctic (Nicholls *et al.*, 2006).

Ice-covered seas can be particularly hazardous for AUV operations, mainly due to the harsh environmental conditions encountered during the launch and recovery process (Stevenson, this volume). Before launch, freezing air temperatures can be extremely disruptive with electronics, batteries and scientific equipment, whilst the open-water recovery point may become refrozen or covered with drifting ice during a mission, putting into doubt the successful recovery of the vehicle. In this instance an acoustic homing system should be available to shepherd the AUV to a safe ice-free area for surfacing and recovery.

Additionally, in terms of safe operation, the vehicle should have onboard a forward-looking sonar to detect objects located at or near the AUV's cruise depth, (e.g. pressure ridges or icebergs that are extending deeply downwards), and a downward-looking sonar to determine the clearance above the seabed (Pebody, this volume). As it is not possible for human operator intervention, in terms of below-surface AUV control, these sensors should be linked to intelligent collision avoidance systems that can either manoeuvre the vehicle safely around these obstacles or cause it to retrace its path back to the launch site.

3. The Challenge for the Future

Work to date has laid the foundation to build the basis for continued AUV operations in the polar oceans. As such the opportunity exists to continue to deliver compelling science with every completed mission. It is reassuring that many scientists are now openly discussing and considering the use of AUVs within the framework of their scientific programmes. Despite this groundswell within the scientific community, the reality is that the use of AUVs in the polar region continues to be a rarity.

The challenge to the polar oceanographic community is to increase the number of missions in the polar seas. To do this, efforts need to be made to increase the profile of AUV operations and address the perceived reliability issues of AUV technology (Griffiths and Trembanis, this volume). There will always be risks associated with the use of an AUV. This is especially true in the polar environment, as demonstrated by the recent loss of the *Autosub2* under the Fimbul Ice Shelf in the Antarctic.

As a result, each funding agency must balance the cost and risk associated with the use of an AUV against the value of the collected data and the potential for new discoveries. It is one of the duties of the polar community to pressure funding agencies to ensure that they do not direct funds to areas considered to be a safer option. This can be achieved through high quality multidiscipline proposals that address the most compelling questions regarding climate change in the polar oceans, deliver the highest return in terms of scientific data and provide the best dissemination of the work into public knowledge. This will ensure AUV operations in the polar seas maintain a high public profile.

Essential in the future development of AUV missions in the polar seas is the transmittance of knowledge and experience from current and past programmes, so that future AUV missions can be planned accordingly. To this end the ECOR* Specialist Panel on Underwater Vehicles AUVs is expected to publish in mid 2007 a guide titled, 'Best practice guide to the use of AUVs in ice covered seas'. This will include case studies from previous users. ECOR will also sponsor a dedicated website to the use of AUVs within ice covered seas.

4. Multidisciplinary

The development of the AUV as an operational tool will continue to evolve in response to user needs. As such vehicle design characteristics will also evolve as a function of capabilities, endurance and mission profile. Smaller sized models will be able to be launched and recovered from holes drilled through sea ice, whereas larger versions will almost certainly need to be released from icebreakers. Regardless of design configuration, the combination of scientific instrument payload that can be carried onboard will

* The Engineering Committee on Oceanic Resources,
see http://www.rina.org.uk/underwater_vehicles_specialist_panel.html

allow the simultaneous investigation of the sea ice, oceanographic and biological properties of the water column in ice-covered seas. This multi-sensor approach to scientific data gathering will enable collaborations and closer contact with scientists from different disciplines, who usually work independent of each other, hence enabling a holistic approach to polar oceanography.

5. AUV Technology Beyond the Polar Seas

While the focus of this chapter is concerned about future campaigns within the ice-covered seas, it is important to mention the use of AUV technology in space exploration. For example Europa is of interest because this satellite of Jupiter is believed to possess an enormous reservoir of subsurface water under a thickness of ice on its surface, which has yet to be quantified. Lessons learnt from the use of AUVs in the polar oceans of earth will enable pioneering step to be made in the exploration of interior oceans that may be present on other planetary bodies and satellites within our solar system and beyond (Stone, this volume). The coupling of space technologists with the AUV community will facilitate advances in both reliability and mission development. This will benefit both communities and continue the scientific investigations and the advancement of our knowledge of the polar oceans. Scientists are currently developing small AUVs for use in the ice-covered liquid lakes that are under the Antarctic ice sheet. Our experience with AUVs is paving the way for advances in fields far removed from polar oceanography.

6. Conclusions

AUVs are an exciting development in the field of polar oceanography. They have the possibility of providing a broader understanding of the changes now occurring within the polar oceans and, in many ways, are superior to manned submarine missions. The continued use of AUVs in the polar oceans needs the perseverance and participation of the entire polar oceanographic community, as well as the continued support of both the funding agencies and the commercial sector. Continued investment in technology development and the training of new staff are essential if we are to maintain and increase our capability to unlock the secrets of the polar oceans. This is also essential if we are to understand the changes that are presently occurring in these regions, across the spectrum of disciplines.

As this technology matures, it is envisaged that these vehicles will make the transition from being an avant-garde technology to being a mainstream scientific instrument. This is the same development cycle that previous state-of-the-art oceanographic instruments have experienced in previous decades (e.g. the APEX float).

Once this transition has been made, it is envisaged that the AUV market will grow dramatically as further commercial and non-commercial applications of this technology are

developed. This will create a self-sustaining feedback cycle that will drive improvements in the technologies associated with both the vehicle and the sensors carried in the payload, as well as additional peripherals. An example of this is the development of rendezvous stations from which AUVs can dock to download data and recharge their batteries before performing another autonomous mission. This will deliver both a temporal and spatial component to the data gathered. Furthermore, one can envisage future AUVs having the capability for adaptive sampling within a programmed mission.

We cannot expect polar missions to drive a significant increase in the AUV market or the associated technological advances, but an increase in awareness and numbers of successful missions will have tangible benefits to the polar community. In turn, this should lead to an increase in polar missions leading to a situation where we can introduce more demanding missions, such as the use of multiple AUVs or the first AUV trans-Arctic crossing.

When this increase in demand for AUVs will manifest itself remains speculative, but I for one will watch the next decade with great interest, as the home of the AUV will always be the polar oceans.

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Autonomous Underwater Vehicle Navigation and Proximity Operations for Deep Phreatic Thermal Explorer (DEPTHX)

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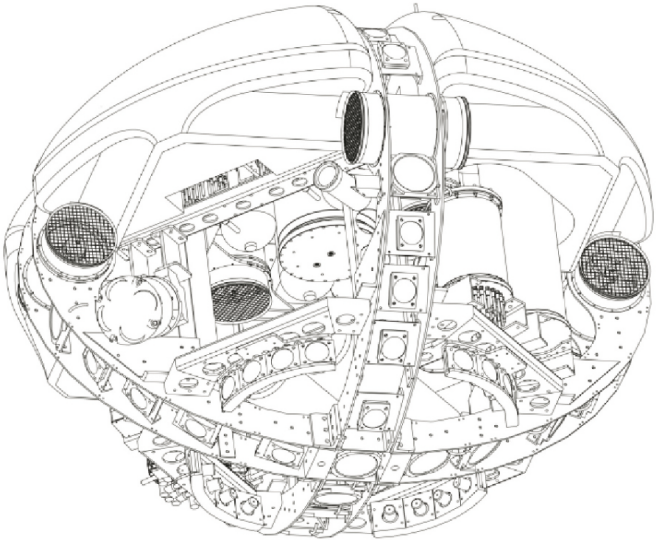
Abstract
This chapter focuses on the issues of navigation, homing and docking in 'overhead' environments in the context of autonomous underwater vehicle (AUV) behaviour. Ocean-going AUVs (as well as unmanned ground vehicles and unmanned air vehicles) have the benefit of the possibility of periodic external navigation corrections to purely proprioceptive (dead-reckoned) position and velocity vector estimates. Sub-ice (as well as subterranean) environments preclude such external aiding unless extraordinary efforts are undertaken to provide a downhole equivalent of global positioning system (GPS) in the form of an ultra-short base line (USBL) or short base line (SBL) array. In general, for truly autonomous navigation over long baseline distances, one cannot assume that such aids will exist or that their validity will only exist within refined zones of operation. One approach that is being undertaken for the NASA Europa lander third stage AUV is that of 3D-SLAM (simultaneous localisation and mapping) as the primary navigation driver. We will present the current implementation of this in the Deep Phreatic Thermal Explorer (DEPTHX) vehicle. Proximity operations (proxops), and the relevant control law implementation for DEPTHX are also discussed.

1. Vehicle Architecture

Deep Phreatic Thermal Explorer (DEPTHX) is a prototype for the NASA Europa mission lander third stage, destined for exploration of the sub-surface ocean of that Jovian moon. Given that no external navigational aiding will be present (precluded by the presence of a 3 to 5 km thick ice cap), novel thinking is required to ensure the success of the mission, which from a science perspective is the detection of the first microbial life off Earth. Current thinking of planetary scientists (Greenberg, 2005; Hussmann, 2006; Chyba and Phillips, 2002) is that the most likely locations for the presence of microbial life on the moons of the outer planets will be either in cracks or fissures in and under ice sheets and on the ocean floor, where gravitational tidal heating may lead to preferentially advantageous locations for sustaining microbial communities. The DEPTHX AUV is designed to explore these environments and to create its own maps that serve as the input to a 3D-SLAM geometric navigation engine.

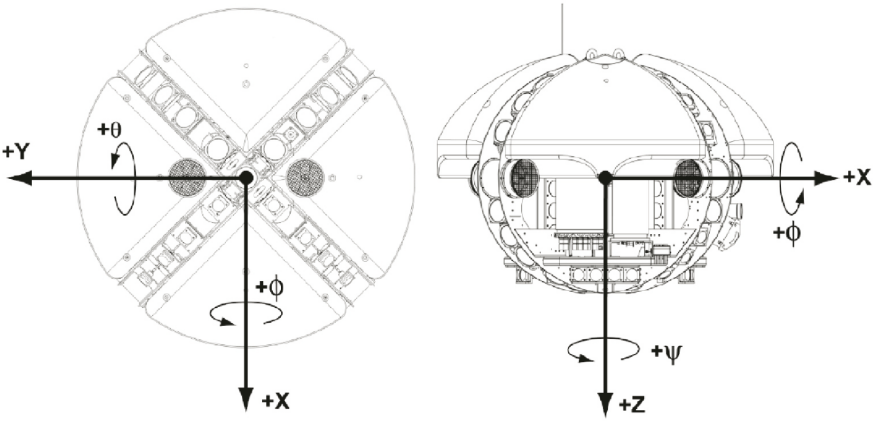
Figure 1: The DEPTHX vehicle minus its science payload



The DEPTHX vehicle (see Figure 1) was expressly designed around the concept of 3D-SLAM, where geometric (sonar) range data are required both in the direction of exploration (for the creation of new maps) and simultaneously in the direction just travelled. Because the orientation of the vehicle relative to the map cannot be predicted ahead of time, the 'geometry engine' of the vehicle needs to view effectively 4π steradians in real time about the vehicle. This forces a different solution than is typically employed on ocean-going AUVs, where the predominant platform of the vehicle is torpedo-shaped and the typical complement of sonars onboard consists of a downward- or upward-looking side-scan or multibeam unit, and perhaps a forward-looking wide beam obstacle avoidance transducer.

An equally important consideration is the propensity for multipath spoofing in a three-dimensional labyrinthine environment, especially for the previously mentioned traditional swath-type bathymetry instruments. We resolved both issues by using an equal-angle distributed array of very narrow beam transducers, mounted on three orthogonal great circle endoskeleton frames, as shown in Figure 1. The transducers were a mix of 200 m (330 kHz) and 100 m (675 kHz) 2-degree beam designs following the successful results reported in Stone *et al.* (2000). A total of 54 such 2-degree beam transducers generate a continuous point cloud about the vehicle. What remains is to incorporate these into a real-time map.

Figure 2: Vehicle coordinate system for the DEPTHX AUV



In order to preclude blind spots the vehicle must, in fact, be capable of simultaneous, real-time observation of the entire 4π steradian solid angle space about the vehicle. From an idealised standpoint, one could imagine a vehicle paved with surface mounted sensors viewing in all directions. From a practical consideration, however, the number of individual sonar transducers will be limited both due to space restrictions on the vehicle and cost considerations. Because of the high degree of multipath signal in cluttered three-dimensional environments, the use of traditional sonar mapping tools (e.g. multibeam, side-scan, Didson) is precluded.

Our approach was to build an array of discrete highly directional beams that could each be equipped with its own digital signal processor for multipath rejection. What remained was to determine the optimal minimum set of transducers. Extensive simulations revealed that an array consisting of three orthogonal 'great circles', with transducers distributed uniformly about the circumference of the circles, produced good navigation data for motion in any direction (Fairfield *et al.*, 2005).

A further consequence of this SLAM-driven requirement was that one could economically (that is, at low energy) build higher density maps relative to the vehicle by simply

spinning it. This behaviour necessarily led to the concept of an axisymmetric vehicle – obtained by revolving a convex shell. This topology class includes spheres and ellipsoids. For drag reduction an ellipsoid was ultimately selected. Figures 1 and 2 show the physical implementation of this concept. In this case, owing to practical fabrication considerations, the horizontal thrusters were mounted at the mid-body circumference of the vehicle, forcing the XY great circle transducer plane lower in the vehicle. The transducer angular insonification pattern, however, still achieves the desired effect. Two vertical thrusters (see Figure 2 left) are clustered close to the vehicle vertical centreline and aligned with ducting cast into the syntactic floatation panels.

2. Dead-Reckoning Navigation

Following the aeronautical standard, we define the right-handed world frame *x*–*y*–*z* axes as north–east–down, with rotations according to the right-hand rule: point along the axis with the thumb of your right hand and curl your fingers, which now point in the direction of positive rotation. For example, a 90-degree rotation around the Z (down) axis leads to facing east. Thus the full 6 degrees of freedom pose of an object in three-dimensional is specified as:

$$\mathrm{p} = [\varphi, \theta, \psi, \mathrm{x}, \mathrm{y}, \mathrm{z}]^{\mathrm{T}}$$

Likewise, define the right-handed vehicle frame *x*–*y*–*z* axes as forward–starboard–down, with roll–pitch–yaw, or φ–θ–ψ, rotations following the right-hand rule. Letting $s\varphi = \sin(\varphi)$, $c\varphi = \cos(\varphi)$, the operations that rotate the vehicle frame to the world frame are: rotate by the roll angle φ around the world *x*-axis, then rotate by the pitch angle θ around the world *y*-axis, then rotate by the yaw angle ψ around the world *z*-axis. The rotation matrix from vehicle to world frame is thus:

$$R_v^w = R_z(\psi)R_y(\theta)R_x(\phi) = \begin{bmatrix} c\psi c\theta & c\psi s\theta s\phi - s\psi c\phi & c\psi s\theta c\phi + s\psi s\phi \\ s\psi c\theta & s\psi s\theta s\phi + c\psi c\phi & s\psi s\theta c\phi - c\psi s\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix}$$

To transform a point $\mathbf{x}^{\mathrm{v}}=[x, y, z]^T$ from vehicle frame to world frame, we have:

$$\mathbf{x}^w = R_v^w \mathbf{x}^v + \mathbf{o}_v^w \quad \text{where } \mathbf{o}_v^w = [x,y,z]^T$$

If we define the homogeneous transformation matrix from vehicle to world frame to be:

$$T_v^w = \begin{bmatrix} & R_v^w & \mathbf{o}_v^w & \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The transformation of a point from the vehicle to world frame can be succinctly expressed as a single matrix multiplication by:

$$\begin{bmatrix} \mathbf{x}^w \\ 1 \end{bmatrix} = T_v^w \begin{bmatrix} \mathbf{x}^v \\ 1 \end{bmatrix}$$

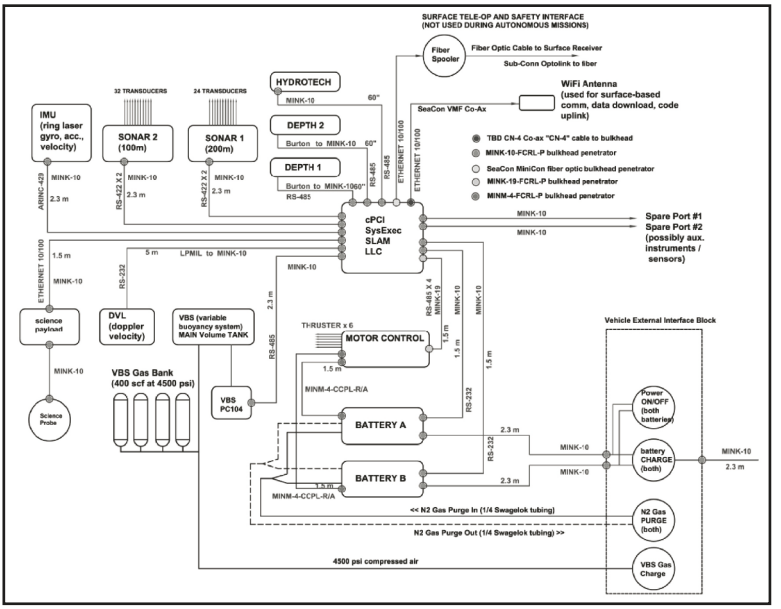


Figure 3: Electrical system architecture for DEPTHX

The DEPTHX vehicle makes use of a number of sensors that provide input into both the control and navigation filters. Figure 3 shows the overall vehicle electrical system architecture, while Figure 4 shows a schematic architecture for the control and navigation subsystem. The primary dead-reckoning sensors consist of a high-grade inertial measurement unit (IMU), a ring laser gyro (RLG), doppler velocity log (DVL) and two high-grade depth sensors. We can define the transformation for the IMU and DVL instrument frames to the world frame by the transformations:

$$T^w_{imu} = T^w_v T^v_{imu} \quad \text{and} \quad T^w_{dvl} = T^w_v T^v_{dvl}$$

Note that much of the time we will be using the rotation matrices, since we will be dealing with quantities like velocity. The DVL measures $v_{\mathrm{dvl}}=[dx, dy, dz]^T$, velocities in the DVL instrument frame. These velocities are rotated into the vehicle frame, taking into account the angular velocities:

$$\mathbf{v}^u = R^v_{dvl}\mathbf{v}^{dvl} - \omega \times \mathbf{o}^{dvl}$$

where $\omega = [\omega x\ \omega y\ \omega z]^T$ are the angular velocities in the vehicle frame (as measured by the IMU), and ω x $\mathbf{o}^{dvl}$ is the cross product of the angular rates and the DVL offset or lever-arm. It is then a simple matter to rotate the vehicle frame velocities into the world frame:

$$\mathbf{v}^w = R^w_v \mathbf{v}^u$$

and then numerically integrate these velocities to get the new dead-reckoned position estimate using Euler's method:

$$\hat{\mathbf{x}}' = \hat{\mathbf{x}} + \int \mathbf{v}^w dt$$

where dt is the integration time step and

$$\hat{\mathbf{x}} = [North, East]^T$$

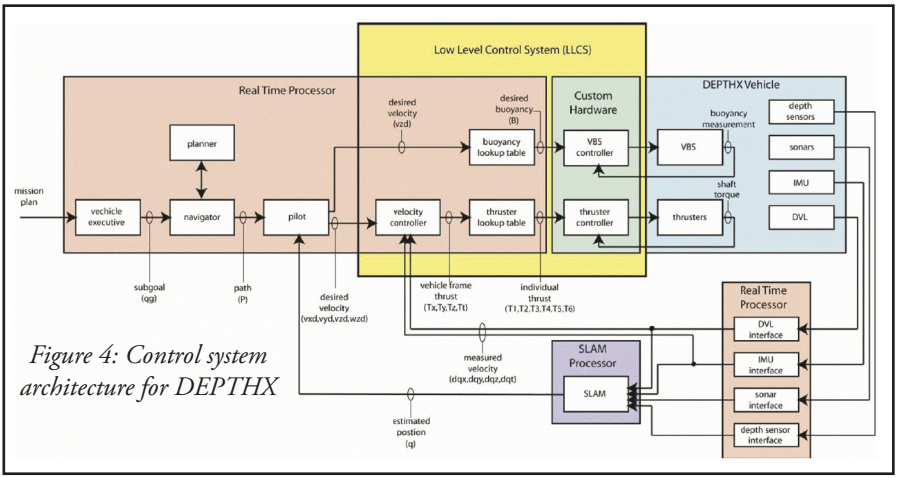


Figure 4: Control system architecture for DEPTHX

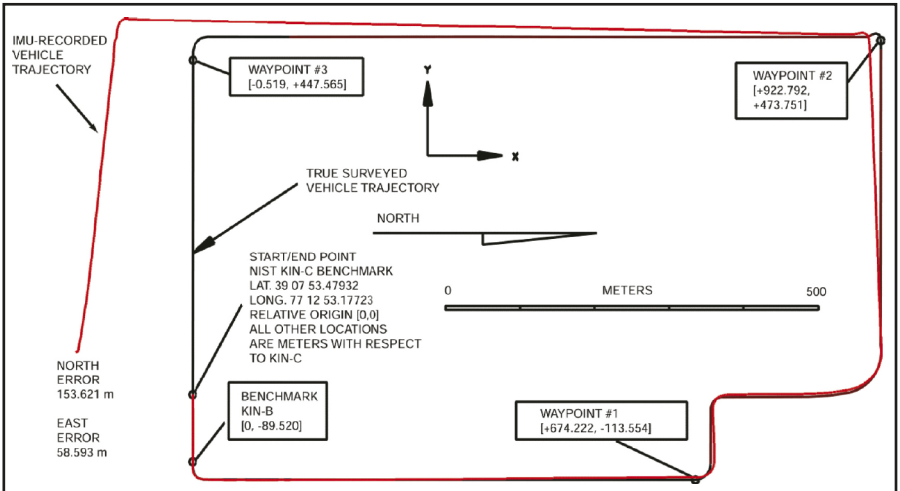


Figure 5: XY drift in IMU-only dead-reckoned position estimate during a 30-minute closed loop

In the DEPTHX implementation of dead reckoning, we fall back to the IMU velocity estimate when DVL measurements are not available. Unlike the DVL velocities, the IMU velocities drift over time, since they are the result of the integration of accelerometers, and this leads to a drift in the position estimate (see Figure 5). When we have good DVL velocities, we use them to estimate and correct for the drift.

Some typical results obtained using only the DEPTHX dead-reckoning navigation system are shown in Figure 6. Under certain circumstances, such an approach can provide good, but not perfect, navigation, approaching a divergence rate of 0.5 percent of distance travelled (Larsen, 2000). DEPTHX is designed for an eight-hour mission at an

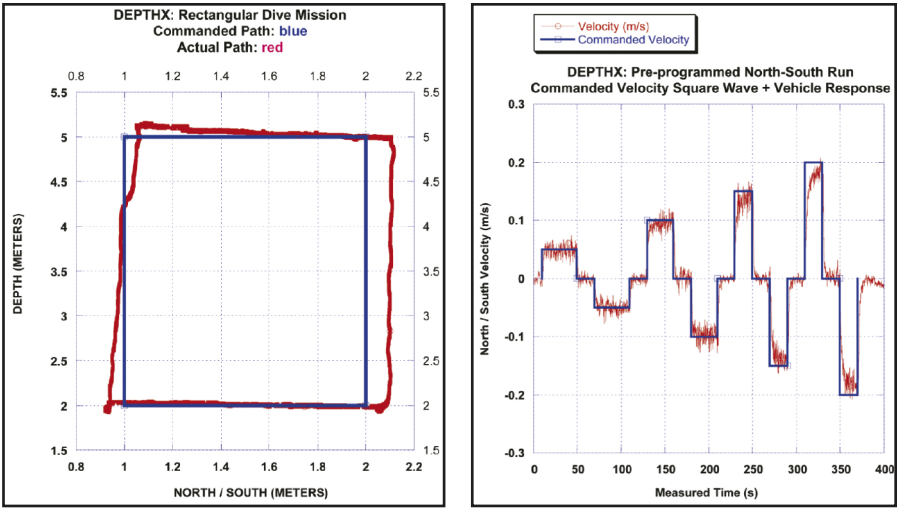


Figure 6: Left, XZ vehicle tracking along a north-south rectangle (varying from 2–5 m depth) as determined by dead reckoning (red) against the commanded path for DEPTHX Right, X (north-south) velocity tracking for the DEPTHX vehicle as measured by the DVL (red) against the commanded behaviour (blue)

average cruising speed of 0.2 $m.s^{-1}$, and thus an exploration range of approximately 5700 m. Over this range, the absolute best one could anticipate from a pure dead-reckoning navigation solution would be on the order of 30 m, which would be unacceptable in a fully three-dimensional labyrinthine environment. But data dropouts from the DVL (e.g. from noise, switching from water column tracking to wall tracking, and loss of lock when too close to a surface) will significantly degrade this position estimate. Thus, for reliable navigation in unknown three-dimensional territory, additional tools are needed.

3. Three-Dimensional Simultaneous Localisation and Mapping

Simultaneous localisation and mapping (SLAM) is the process of building a map of the environment from sensor data while simultaneously using that map to localise the vehicle. SLAM is a very active field, but most work has been in indoor environments (like office hallways), although there is a growing amount of work in more extreme outdoor environments (among others, see Smith *et al.*, 1990; Leonard *et al.*, 1998; Williams *et al.*, 2000; Newman *et al.*, 2003; Williams and Mahon, 2004; Eustice *et al.*, 2005). Furthermore, most SLAM approaches use feature-based maps that depend on high resolution sensor data to enable feature recognition. In underwater environments, it is not generally possible to obtain the high resolution needed for feature recognition.

For DEPTHX we have developed a data-driven representation of the environment in which we employ a probabilistic algorithm that tracks a best estimate of the vehicle

trajectory (pose) and a three-dimensional map of the environment. We begin with a description of our three-dimensional map data structure, and then continue with an overview of our implementation of a Rao-Blackwellized Particle Filter (RBPF) (Murphy, 1999; Doucet *et al.*, 2000), the method we use to estimate the vehicle pose and the map. We will not attempt to derive this implementation here, but rather will give a brief introductory overview, see Fairfield *et al.* (2005, 2006, 2007) for a complete derivation.

3.1 Compact Three-Dimensional Maps

The sonar measurements are noisy and unable to resolve fine features, but over time they do provide information about the environment around the vehicle. In order to combine the individual sonar measurements, the DEPTHX vehicle uses a three-dimensional evidence grid (see Martin and Moravec (1996) for a description of the classic two-dimensional evidence grid). In a three-dimensional evidence grid, space is uniformly discretised into cubic voxel elements. As measurements are made, the evidence they provide about the occupancy of each voxel is entered, or inserted, into the map (see Figure 7).

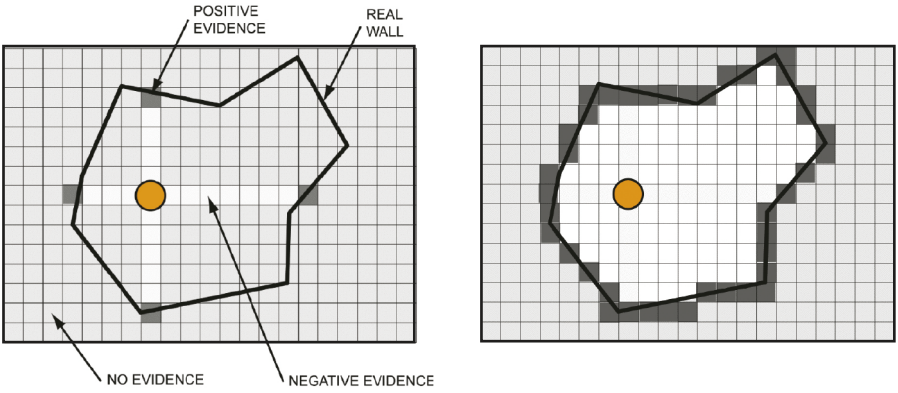


Figure 7: Left, a two-dimensional slice of a three-dimensional evidence grid following four sonar pings. Right, a two-dimensional slice of a three-dimensional evidence grid following hundreds of pings. Note that in this model the darker the voxel, the higher the probability that a cell is occupied. Clear (white) spaces have a high probability of being empty, while the light grey cells are unknown and have an equal probability of being occupied or empty. The circle at the centre of the cross section represents the true vehicle position

A measurement model is used to determine how a particular sonar measurement affects the map. We modelled the 54 individual sonar transducers as producing 2-degree cones projecting from the vehicle (see Figure 8a). Given a particular range measurement, our model states that voxels within the cone are probably empty, and voxels at the end of the cone are probably occupied, since something produced the measured reflection. A modified Bresenham three-dimensional ray tracing algorithm (Bresenham, 1965) is used to merge these probabilities with the information already contained in the three-dimensiona; evidence grid, according to a Bayesian update rule (see Figures 7 and 8b).

A major drawback of the three-dimensional evidence grid approach is that the memory required to store the grids increases as the cube of the size of the map. For reasonable map sizes and resolutions, the memory requirements quickly become intractable, especially considering that the particle filter described below requires hundreds of maps. To circumvent this storage and processing problem we use the deferred reference counting octree (DRCO) data structure described by Fairfield *et al.* (2007). The DRCO exploits shared regions between particle maps and efficiently represents sparse volumes, yielding a significant performance boost that allows us to represent maps that would not even ft into memory as a uniform array.

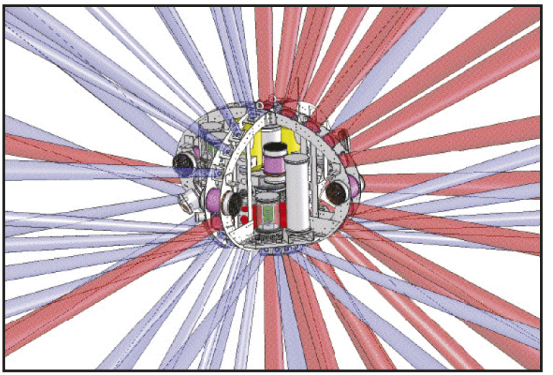
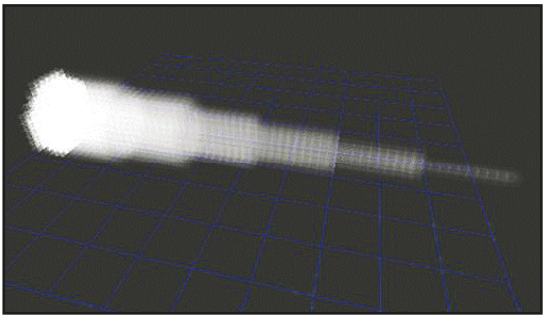


Figure 8a (above): Discrete beam sonar model for DEPTHX. The model includes 24 obstacle avoidance 200 m range 2-degree beam transducers and 30 imaging 100 m range 1.75-degree beam transducers arrayed on 18-degree radial separations.

8b (below): A single sonar beam model as represented in an evidence grid



3.2 Three-Dimensional Particle Filtering

The goal of SLAM is to estimate the probability distribution at time, *t*, over all possible vehicle states, *s*, and world maps, Θ, using all previous sensor measurements, *Zt*, and control commands, *Ut*. This is known as the SLAM posterior:

$p(s, \Theta, Zt, Ut)$

While usually intractable to solve in closed form, the SLAM posterior can be factored (Murphy, 1999) as a combination of the distribution of vehicle trajectories and the distribution of maps. It is often very hard to express these distributions in closed form, and so a particle filter maintains a discrete approximation of the SLAM posterior using a large set of samples, or particles. Since the posterior is factorised into trajectory and map distributions, the particles are actually a specific trajectory and map pair. In fact, given a vehicle trajectory, the map can be iteratively updated (as previously discussed). This is known as a Rao-Blackwell factorisation (Doucet *et al.*, 2000), and it has many useful properties.

The particle filter algorithm has the following steps:

- **Initialise:** The particles start with their poses initialised according to some initial distribution and their maps (possibly) containing some prior information about the world. This is called the *prior distribution*.
- **Predict:** The dead-reckoned position innovation is computed using the navigation sensors (as previously described). A new pose is predicted for each particle using a vehicle motion model. This new distribution of the particles is called the *proposal distribution*.
- **Weight:** A weight is computed for each particle by comparing the real range measurements to ranges simulated by ray-tracing with the particle pose and map. A particle that has a pose and map that are consistent with the real range measurements will have a high weight, while particles that are inconsistent will have low weights.
- **Resample:** The algorithm resamples the set of particles according to the weights, such that particles with low weights are likely to be discarded, and particles with high weights are likely to be duplicated (poses and maps). The set of particles is now our new estimate of the new SLAM posterior.
- **Update:** The measurements are inserted into the particle maps (as previously described) to update the evidence of all the voxels that lie in the conic sonar beam model of each measurement relative to the particle position.
- **Estimate:** Generate a position estimate from the particles; when SLAM is being used to provide a pose for the rest of the vehicle control software, we usually want to turn the set particles into a single point estimate.

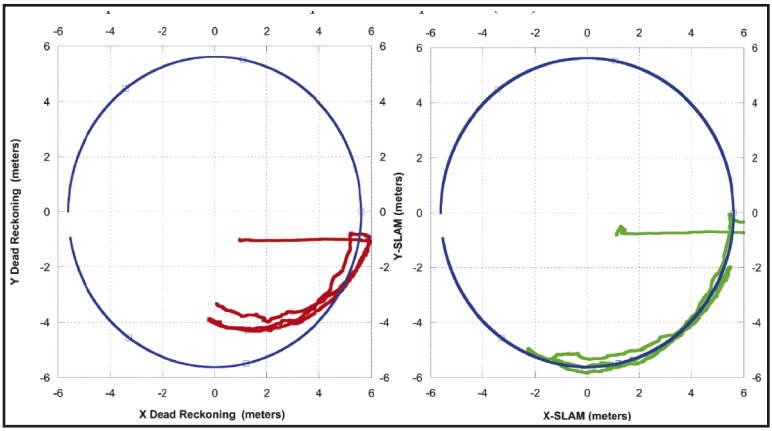


Figure 9: Tank testing of dead reckoning and SLAM localisation. The vehicle was programmed to execute a proximity operation starting from coordinates [1, –1], proceeding to a wall stand-off distance of 2 m in a circular test tank. The vehicle was then to follow the wall clockwise to a point 90 degrees from the contact point, and then cycle back and forth along the same segment of the wall, while maintaining a stand-off distance of 2 m. The blue circle represents the 2 m target stand-off circle. The red line in the left hand figure represents the dead-reckoned vehicle trajectory, while the green line in the right hand figure represents the SLAM localised vehicle trajectory

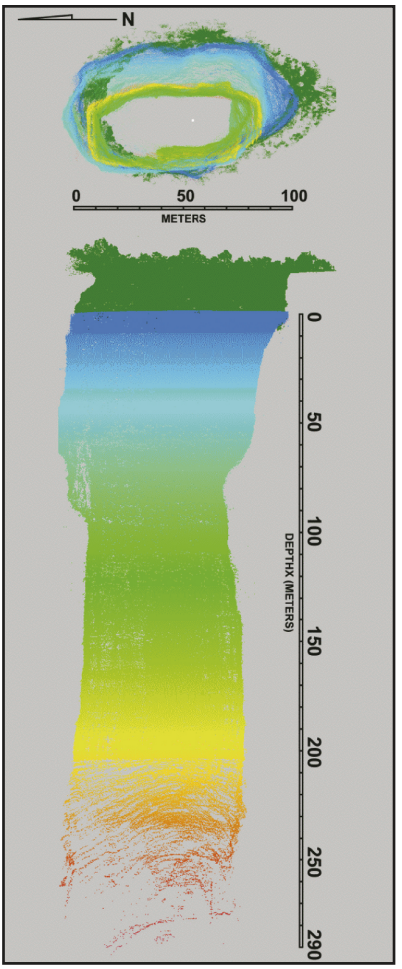
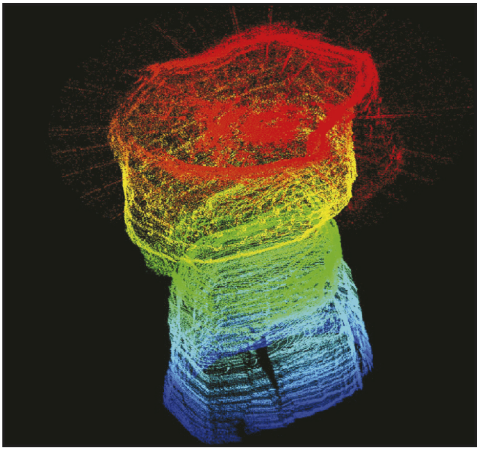


Figure 10: The field test site for the DEPTHX vehicle is the Zacatón cenote in North Eastern Mexico. It is currently the world's deepest known cenote and is a water-filled hydrothermal vent of unknown length and depth. The first map of this cenote was created using a subset of the DEPTHX core navigation and imaging systems configured as a drop sonde. An isometric view of the resulting registered point cloud is shown below. A total of more than 4 million three-dimensional points were acquired during seven drop missions. Note: the dark green portion of the map was created using laser radar and represents the air-filled portion of the cenote and the surrounding jungle; the blue level represents the beginning of the sonar data, which are thence colour coded with increasing depth



In the tests we have conducted thus far (Fairfield *et al.*, 2007) using real sonar data, approximately 200 particles are needed to achieve our target 1 m localisation accuracy, which is readily supported in real time by the DEPTHX onboard SLAM processor.

Figures 9 and 10 provide some quantitative results of the effectiveness our SLAM algorithm. A dramatic comparison between the dead-reckoned navigation solution and that of SLAM is shown in Figure 9, where the dead-reckoned solution degrades during a proximity operation mission that tracks the wall of a circular test tank. By the conclusion of the mission the dead-reckoned solution drifted more than 3 m from truth, due to poor DVL data while the SLAM solution correctly tracked the true trajectory. In Figure 10 we localised the vehicle using sonar data collected from the Zacatón cenote in Mexico to a depth of –290 m. The mean spherical error probable (SEP) was on the order of 0.5 m.

4. Proximity Operations (Proxops)

DEPTHX is designed to conduct operations in close proximity of the walls of Zacaton to facilitate autonomous science missions to search for, collect and classify microorganisms. Examples of such missions include surveying an area for visually interesting features and obtaining core samples from the limestone walls. Specific high level commands that would be executed by the system executive include:

- **ApproachWall** (d_0, θ_0): Approach the nearest wall at a stand-off distance of d_0 and a relative heading of θ_0 while maintaining constant depth. The relative heading is defined to be zero when the vehicle directly faces the wall
- **WallFollowVertical** (Δz): Move downward along wall by the distance Δz while maintaining constant stand-off distance and relative heading
- **WallFollowLateral** (Δl): Move rightward along wall by the distance Δl while maintaining constant depth, stand-off distance and relative heading.

In order to provide these capabilities, we have developed a collection of reactive motion primitives that we call the proxops controller. The proxops controller uses feedback from the mapping sonars to fit a plane to the nearest wall (Figure 11a), and then issues a velocity command to the vehicle in order to achieve the desired goal. The velocity command is sent to a low-level velocity controller that uses IMU and DVL feedback to determine the thruster inputs necessary to track the desired velocity command.

At the heart of the proxops controller is an inverted dynamics controller derived from the kinematic equations of motion of the vehicle. The equations of motion are derived from the controller commands:

d_0 – Desired wall distance

l_0 – Desired lateral travel

θ_0 – Desired wall angle

with the controller parameters:

γd – Wall distance convergence rate

γl – Lateral convergence rate

$\gamma\theta$ – Wall angle convergence rate

$kd\text{x}$ – Forward damping gain

kdy – Lateral damping gain

$kd\omega$ –Wall angle damping gain

There is the assumption that the wall in front of the vehicle is approximately planar. Under this assumption, the stand-off distance, d, relative heading, θ, and lateral position, l. can be defined as shown in Figure 11b. This geometry can be used to determine the derivatives of these quantities as a function of vehicle velocity:

$$\dot{d} = -vx + vy\tan\theta + d\omega\tan\theta$$

$$\dot{l} = vx\sin\theta + vy\cos\theta + \dot{d}\omega\cos\theta + \dot{d}\sin\theta$$

$$\dot{\theta} = \omega$$

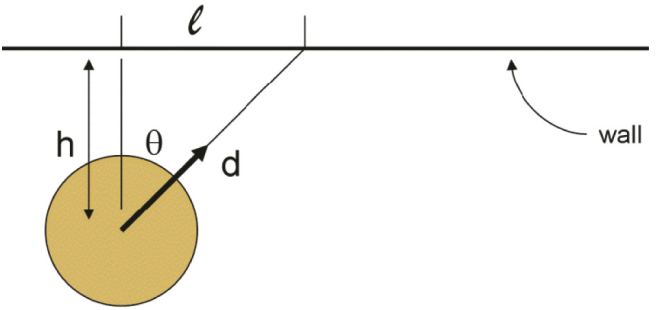
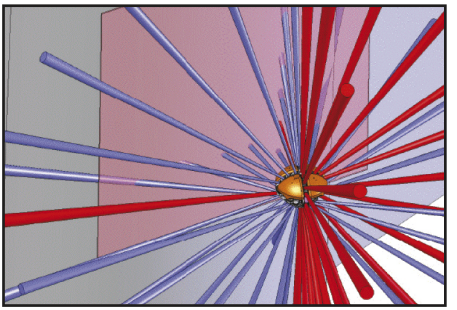


Figure 11a (below): Proximity operations – fitting tangent plane to the target surface

11b (left): Proximity operations – definition of control parameters



where *vx*, *vy* and ω are respectively the forward, starboard and angular velocities of the vehicle.

Using these equations of motion, we determine a proxies control law that maps current wall geometry (*d*, θ and *l*) and vehicle velocity measurements (*vx*, *vy* and ω) into desired vehicle velocities (vx_d, vy_d and ω_d):

$$vx_d = \gamma_d(d - d_0) + vy\omega\tan\theta + d\omega\tan\theta - k_{dx}vx$$

$$vy_d = -\frac{\omega d(\cos\theta + \sin\theta\tan\theta)}{\cos\theta + \omega\sin\theta\tan\theta} + \frac{\gamma_l(l - l_0)}{\cos\theta + \omega\sin\theta\tan\theta} - k_{dy}v_y$$

$$\omega_d = -\gamma_\theta(\theta - \theta_0) - k_{d\omega}\omega$$

where the controller parameters and commands are defined above.

This controller assures exponential convergence of the proxops variables *d*, *l* and θ to d_0, l_0 and θ_0, respectively. This can be verified by substituting the desired velocities into the equations of motion. The damping terms are hand-tuned to account for the fact that the underlying velocity controller is not perfect (e.g. that ω_d is not equal to ω). This control law can be used to achieve all of the desired proxops behaviours by choosing appropriate values for d_0, l_0 and θ_0.

Figures 12 and 13 depict the vehicle response to two types of proxops commands. In both cases these tests were conducted in the same 15 m diameter neutral buoyancy facility used for the SLAM navigation results reported earlier.

In Figure 12 the plots show the vehicle response to an ApproachWall command. The vehicle starts at a distance of 4 m from the wall and is commanded to move to a stand-off distance of 2 m at approximately t = 4 s. The vehicle reaches its goal at approximately t = 46 s. The relative heading and lateral motion are maintained at zero during this manoeuvre.

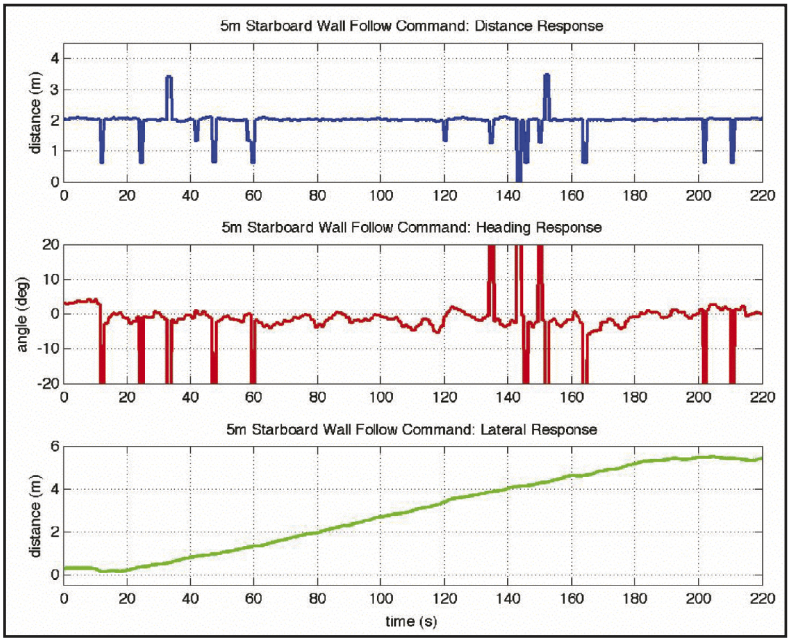
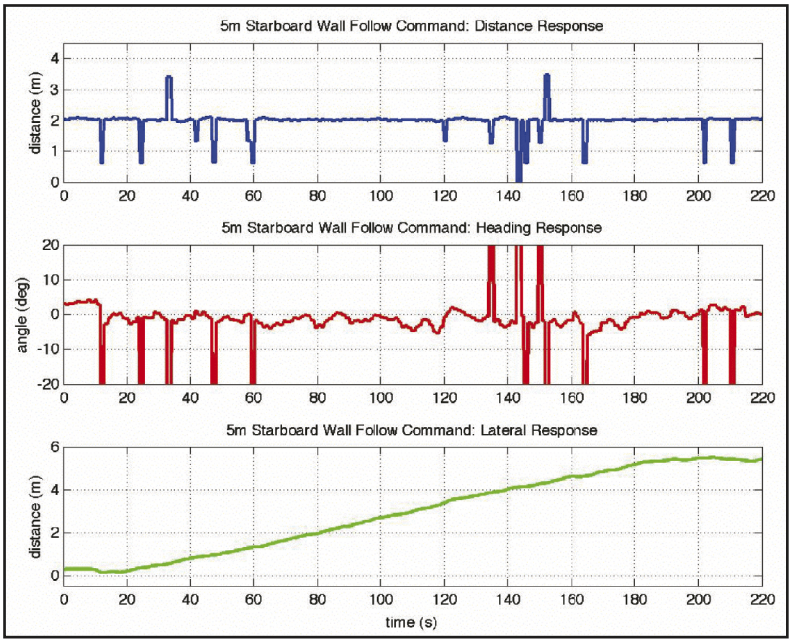


Figure 12 (above): Vehicle response to ApproachWall command

Figure 13 (below): Vehicle response to WallFollowLateral command



In Figure 13 the response to a WallFollowLateral command is shown. Here the vehicle is commanded to follow the wall laterally in the starboard direction for a distance of 5 m. The command is issued at t = 20 s, and the goal is reached at about t = 190 s. Wall distance and angle are held constant. Note that there is significant noise in the distance and angle measurements due to noisy sonar data (a function of the test tank geometry and the frequency of the tranducers). A noise filter is currently being implemented, but nonetheless the controller performs well in the presence of this noise.

5. Summary and Conclusions

DEPTHX was designed to test two of the fundamental capabilities that will be required of any autonomous robotic system exploring sub-surface oceans of the moons of the outer solar system:

1) to be able to explore into unknown territory with no external navigation aiding, create three-dimensional maps of the explored world and to return home (to a data uplink port) using its own just-created maps; and
2) to attain a degree of science autonomy that will enable a behaviour-based AUV to 'sniff' likely locations for the presence of microbial life, and thence locate potential microbial life, verify that what is located is alive, collect, analyse and report home on what is found. It is the first criteria that has driven the need for more sophisticated forms of autonomous navigation. These same navigational tools will find use here on Earth for sub-ice navigation in Artic and Antarctic zones.

Although DEPTHX is a purely experimental science platform, the results thus far from the hybrid navigation and proxops subsystems suggest that the vehicle, and its descendents, will be up to the challenge of exploring Europa and other outer planet moons while potentially providing the first compelling quantitative evidence of life off Earth.

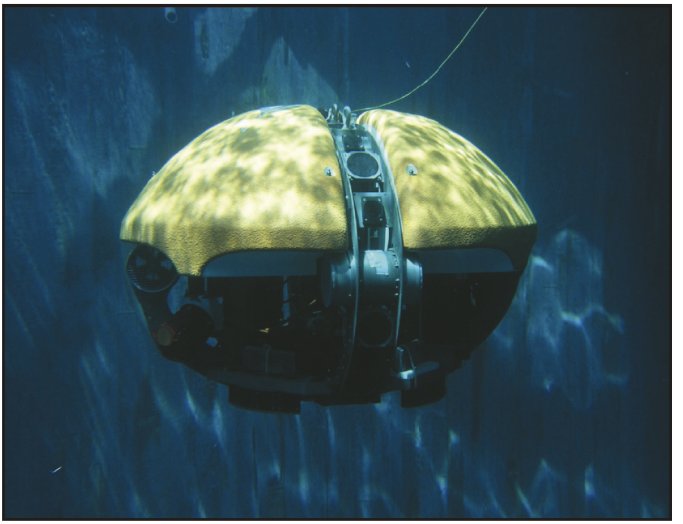


Figure 16: DEPTHX undergoing underwater field tests, October 2006. Note: the small line leading to the vehicle is a fibre-optic data link for observing machine autonomous decision–making, as well as for emergency stop. During actual missions the vehicle will have no data link

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Political/Economic Drivers: Potential for AUV Technologies in United Nations Convention on the Law of the Sea (UNCLOS)

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Abstract
The United Nations Convention on the Law of the Sea (UNCLOS) provides a framework of governance for the world's oceans with respect to the rights and responsibilities of coastal states and other users of maritime space. The rate of acquisition of marine geological and geophysical data to support entitlement to territorial sovereignty – especially that concerned with extending continental shelf areas beyond 200 nautical miles under Article 76 of UNCLOS – has been steadily increasing in recent years in response to approaching deadlines enshrined in the Convention. The expense and logistical difficulties associated with data collection in problematic shelf/margin settings (for example, ice-affected ocean basins) invites the application of autonomous underwater vehicle (AUV) technology to secure cost-effective and accurate datasets. Single-beam and multibeam bathymetric echosounder data for the determination of key Article 76 criteria, such as 'foot of continental slope' and the 2500 m isobath; and/or high resolution seismic profiler (3.5 kHz or equivalent) to confirm sediment sequence continuity are all capabilities already embraced by of a range of AUV types. Seismic reflection profiling, perhaps in a mode combined with surface seismic source, now presents the next challenge for the use of AUVs in difficult or frontier areas.

Theseus on Ice Operations

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Abstract

Commencing in 1988, joint Canada/United States ICESHELF experiments were executed in the Lincoln Sea, north of Ellesmere Island, North West Territories, Canada. These experiments were designed to resolve various aspects of underwater system design and installation in ice-covered waters. This was followed in 1992 by a joint Canada/US undertaking, sponsored by the US Department of Defense and the Canadian Department of National Defence, to install a bottom-mounted research system and associated cable to shore, based on design concepts and lessons learned from the previous work.

To support this project, the autonomous underwater vehicle (AUV) *Theseus* was developed. Built from 1992 to 1996 by International Submarine Engineering Research and Defence Research & Development, Canada, the *Theseus* vehicle is one of the world's largest AUVs. The vehicle was designed to lay up to 220 km of fibre-optic cable in ice-covered waters of between 50 m depth at the launch site to between 500 and 700 m at the array site.

Monterey Bay Aquarium Research Institute's AUV Experience

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Abstract

Beginning in 1999, Monterey Bay Aquarium Research Institute (MBARI) began developing unmanned and untethered vehicles, called autonomous underwater vehicles (AUV), to increase the quality and resolution of existing ocean survey programmes, while at the same time reducing the associated costs of these operations. Knowing that there would be demand for diverse payloads, MBARI engineers created a fundamentally modular vehicle that could be quickly reconfigured to host a number of payloads without modifying basic units – such as the propulsion, navigation, power, control and emergency location systems. The Dorado class AUV has diameter of 21 in and can be as short as 8 ft or as long as 21 ft, depending on the mission. The first Dorado was operated in late 2001 to measure the inflow of water into the Arctic basin through the Fram Strait, and provided the basic template for MBARI Dorado-class AUVs.

Since then, variants of the basic vehicle design have been constructed for three types of mission. The first system to come online incorporates a variety of physical, bio-optical and chemical sensors into a platform with 20 hour endurance and Iridium satellite telemetry. MBARI operates this vehicle as an unattended mid-water survey platform, performing regular transects as part of a time series monitoring programme. It is currently developing an *in situ* water sampler to return pristine seawater samples to shore for laboratory analysis.

The second vehicle constructed is a 6000 m geophysical mapping vehicle, equipped with a multibeam echosounder, sub-bottom profiler, and side-scan sonar. The vehicle is capable of performing precision navigation using a doppler-aided inertial navigation system, and can communicate with the surface via a low frequency acoustic modem. The data collected so far has demonstrated the ability to map the seafloor to better than 0.3 m resolution.

MBARI's current development work focuses on constructing an AUV docking system, allowing a Dorado vehicle to connect to seafloor observatories. The system utilises a 4000 m rated ultra-short base line (USBL) system to home into the dock, and an inductive charging system to transfer power. Initial testing of the homing system has demonstrated a high degree of repeatability.

Operational Feedbacks and Innovations for the AsterX AUV and Victor 6000 ROV

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Abstract

This contribution describes the status of the operational ROV Victor 6000 and the 3000 m depth AUV AsterX operated by IFREMER. Victor 6000 is part of a system integrating a 'scientific module', winch and cable, dead weight and umbilical, positioning subsystem through acoustic ultra short base line (USBL) and all the exploitation software for the data and dive management. In 2005 the system has been equipped with a second module dedicated to high resolution mapping of the sea bottom, with acoustical and optical devices. Recent key missions on margins, ridges and for the installation of the ANTARES Neutrino Telescope illustrate the capability.

The first IFREMER AUV, named AsterX, is 4.5 m in length with a diameter of 0.69 m. Depending on the payload, its weight is between 600 and 800 kg in air, with a diving depth of 3000 m. Its cruising speed is between 0.5 to 2.5 $m.s^{-1}$. The AUV is capable of carrying various payloads in its payload sections for a wide spectrum of applications. The vehicle can cruise up to 100 km range. For coastal applications this vehicle is operated by a limited crew, possibly from small non-specialised or opportunity vessels. The vehicle has made numerous cruises in the Mediterranean Sea and in the Atlantic onboard IFREMER ships in 2004. Numerous requests to use it on German ships (missions on the RV *Meteor* in 2006 and on the AWI RV *Heincke* in 2005) and more than 200 days at sea were requested in 2006.

A second vehicle will be designed and built in 2006. Cross cooperation with the Alfred Wegener Institute, Memorial University in St Johns, Canada, and the University of Southern Mississippi was active in 2006. The second vehicle, optimised from AsterX design in terms of maintenance costs, named IDEFx, is being built. Results with a multibeam sounder mapping slope instabilities in the Mediterranean Sea, with EK60 fishery echosounders in the North Sea, and with physical sensors in the Atlantic, illustrate the mission diversity and capability, with scientific results, and a specific analysis of the operational cost will be presented.