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AUVs as research vessels: the pros and cons.

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Traditional ocean going research vessels have advanced considerably over the last century. However, as marine sampling platforms they suffer from some major shortcomings related to their large size and surface restriction. Autonomous underwater vehicles (AUVs) are small unmanned submarines which have emerged over the past ten years as alternative platforms. Currently, there are over 75 AUVs either under development or in operation in the offshore industries of mineral exploration, in the military, and in applied and academic oceanographic science. This paper reviews the application of AUVs to marine research. Compared to traditional research vessel platforms, AUVs are able to sample previously impenetrable environments such as the sea surface, the deep sea and under sea ice. Furthermore, AUVs are typically small, very quiet, and have the potential to operate at low cost and be unconstrained by the vagaries of weather. Examples of how these traits may be utilised in marine science are given with reference to previous work and to potential future applications. However, before many of the more prospective applications can be accomplished, advances in AUV power source technology are required to increase the range of operation. The paper reviews current power sources for AUVs and examines other developments which will overcome many of the limitations currently inhibiting the wider application of AUVs for gathering data in marine science.

Keywords: AUV, autonomous underwater vehicles, fisheries, oceanography, power sources.

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Introduction

During the 20th century, research vessels (RVs) were the principal platforms for the collection of marine science data at sea. Towards the latter half of the century, a number of alternative platforms became established as, in some cases, better means for collecting particular types of data. Satellites (Johannessen *et al*. 2000) are used to collect synoptic and large scale high resolution information from the visible, infra red and microwave portions of the electromagnetic spectrum. These provide ocean colour (for phytoplankton standing stock and suspended materials), sea surface temperature and altimetry data (for sea level, sea roughness, wind speed and direction and currents) respectively. A variety of data are collected from ships of opportunity (see Rossby 2001 for a brief review), including the significant time series from the Continuous Plankton Recorder surveys (Reid *et al.* 1998). Fishing vessels can also be used to gather scientific data, either by charter or by providing them with equipment and instruction (Melvin *et al.* 2002). Drifting and fixed buoys collect a multitude of hydrographic (e.g. Smart Buoys, Mills *et al.* 2002) and biological (Holliday *et al.* 1998) data. These platforms provide extended data series, either in time or space, to complement RV data, but neither individually nor collectively, could they be expected to replace RVs.

RVs have benefited from numerous improvements over the last century. Modern vessels are designed to be powerful, acoustically quiet, with integrated electric systems, dynamic positioning, and an array of deck gear (winches, cranes, A-frames etc.) and cables (Graf von Spee and Ollier 2001). The ratio of crew to scientists has declined significantly over the last century (Currie 1983): on HMS *Challenger* (1872-1876) it was 40:1; on RRS *Discovery* (1928-1962), 4:1; and on FRV *Scotia* (1998- present) it is close to 1:1. This ratio is now set to invert: e.g. R/V *Atlantis* has the Automatic Centralised Control Unmanned (ACCU) rating for further manpower savings; it has a crew of 22 and can carry 37 scientists. One major change being considered for future RV designs is the use of twin hulls, employed, for example, in Small Waterplane Area Twin Hull (SWATH) vessels (Atkinson 2001). These provide enhanced stability to enable better and prolonged performance in heavy weather and have more useable deck space; but have excessive draft and require higher propulsion power.

Despite any such improvements there are some unassailable shortcomings associated with most ocean-going RVs. Such vessels tend to be large (>50 m) and, therefore, incur a large capital investment to build and annual investments for maintenance. In spite of the improvements in the crew:scientists ratio they still require a sizeable dedicated crew of watch keepers, engineers, deck hands and support staff; in addition to the scientists. RVs continue, therefore, to be expensive: the replacement for the new FRV *Cirolana* is expected to cost in the region of €36M; and running costs for European FRVs are in the region of €10k per day. Regardless of their design, the operation of RVs, in being limited to surface waters, is hampered by adverse weather conditions and cruise days are often lost to bad weather. In some areas, at some times of the year, it may be impractical to consider operating RVs at all. In the longer term this may deteriorate: for example, climate predictions for the UK suggest that the frequency of gale-force wind events may increase by up to 30% (CCIRG 1996), imposing further restrictions on survey time by RVs. Another factor which may limit RV survey time, at least in the European Union, is the forthcoming restriction on working time. This will either cause research institutes to employ more staff to cover the available time, or reduce working time. An example of the latter is the Dutch RV *Tridens* which is obliged to dock into port at weekends (Couperus, RIVO, Netherlands, *pers. comm.*). In either case, the result is a decrease in survey efficiency (less effective ship time per unit cost); this, paradoxically, will impinge adversely on the gains made in reducing the crew:scientists ratio.

It is undoubtedly because of this expense that available shiptime on RVs is restrictive and competitive. In the EU at least, RV capacity is likely to remain the same as at present (Graf von Spee and Ollier 2001). Marine scientists are not, therefore, in the best position to take full advantage of the advances in computing power, information technology and sensor development which have made it possible to process immense volumes of data to use in the creation of realistic scientific models. In fisheries research, fishery independent (RV) data are becoming increasingly important in the light of growing concerns about the quality of the ‘fishery dependent’ [catch] data that comprise the primary elements in assessment models (Patterson 1998). Learning the lessons from the collapse of Canadian cod stocks, key proponents of assessment methodology now concede that there is a continued need to invest in survey (RV) indices of abundance and that improvement may come from direct technological approaches to fish counting using sonar (Walters and Maguire 1996). A similar realisation dawned on oceanographers in the early 90s when it became clear that conventional sampling devices would not be able to supply data of sufficient quantity and quality to model the oceans influence on climate (Griffiths 1992). Demands on RV data are therefore increasing, at a time when RV time is stagnant at best and possibly decreasing.

The restriction of RVs to surface waters brings about another limitation: data gathered beyond the surface waters must be done so remotely. In the case of hydrographic measurements the only disadvantage of this is the time taken for deployment and recovery of sensors. In the case of deep-sea fauna it is difficult to take measurements unless the organisms are sessile. To date, for example, one of the largest animals we know about has yet to be observed in its natural habitat: giant squid (*Architeuthis sp.*) are only known from strandings, occasional trawl catches, or from examinations of sperm whale stomach contents (Collins 1998). Observations of deep-sea fish require the deployment of alternative platforms from RVs, such as submersibles or landers (Priede and Bagley 2000). The deep sea is one marine environment of rapidly growing interest where RVs struggle to obtain reliable data, particularly on active marine fauna; others include under sea-ice, and the sea surface.

Finally, because the demand and expense of research cruises are so great, RVs generally require booking many months in advance. With the exception of major catastrophic events of national importance (such as oil spills) the opportunities to investigate *ad hoc* events of importance are restricted, if not completely impossible, by RV planning schedules. Such sporadic events might include sea surface temperature anomalies, algal blooms, fish kills, exceptional spawning events and other unexpected aggregations or disappearances of marine fauna.

As ICES moves into its second century there is scope for more efficient (in terms of capital and running costs) and more flexible (for sampling in time and space) sea-going data gathering platforms than the huge, labour intensive RVs that have been the mainstay of oceanic marine science for so long. One possible alternative, at least for some tasks, is the Autonomous Underwater Vehicle (AUV). AUVs could provide solutions to many of the limitations associated with sampling from conventional RVs. AUVs were once considered little more than engineering curiosities, but now the technological advancements required for their reliable deployment, mission control, performance and recovery have been achieved (Millard *et al.* 1998). The aim of this paper is to describe how AUVs can and have been used to overcome some of the RV limitations described above, and to cast an eye into future developments which may make AUVs routine platforms for marine science.

Autonomous Underwater Vehicles

AUVs are relatively small, self propelled, untethered, and unmanned vehicles, that can operate wholly underwater beyond the control and communication of any support facility. They are usually pre-programmed to conduct a variety of unattended underwater ‘missions’, and may be launched and recovered from the shore or at sea. They exist under a number of model-specific aliases and are sometimes also classed as untethered unmanned vehicles or unmanned undersea vehicles (both UUV). Typically they are torpedo shaped of the order of 2-10 m in length and 0.2-1.3 m in diameter. The UK’s Autosub (Fig. 1) is typical of the design of many AUVs. Most of the payload space is taken up with the propulsion energy source and command and control instrumentation, which, naturally, need waterproofing in housings which vary in

Figure 1. The AUV *Autosub* attached to its deployment cradle. The vehicle is 6.8 m long and 0.9 m in diameter. In this case two acoustic transducers (38 kHz and 120 kHz) are mounted on the dorsal side (**1**). The beacon (**2**) is for acoustic telemetry and the antennae at the rear (**3**) are for GPS, VHF, Argos and GSM communications.

design according to the operational depth. Most AUVs can operate to 200 or so metres, with some operating beyond 5000 m.

The first AUVs were developed in the late 1960s by the University of Washington (Busby 1977) for oceanographic research (SPURV) and military exploration under ice (UARS): these were successfully trialed in the early 1970's. The 1980's saw a proliferation of AUV technology: Busby (1990) notes that whereas in 1987 there were 23 AUV projects, this had risen to 40 by 1990. Notable AUVs in operation included IFREMER's deep diving *Epaulard*, ISE Ltd.'s ARCS, the Soviet MT-88, and several vehicles supported by the US Navy (e.g. UUVs, B-1, CSTV). More AUVs were developed in the 1990s under a number of programmes which aimed to go beyond vehicle development towards achieving a variety of tasks. The MIT *Oydessy* vehicles undertook a number of oceanographic surveys (e.g. Nadis 1997); ISE Ltd.'s *Theseus* completed a 350 km mission to lay a fibre optic cable under sea ice (Ferguson *et al.* 1999); and Florida University's Ocean Explorer vehicles made measurements of ocean turbulence (Dhanak and Holappa 1996). In the UK, the NERC started its *Autosub* project in 1987 (McCartney and Collar 1990), had a vehicle ready by 1997 (Millard *et al.* 1998), and in 1999, started a thematic programme which addressed a variety of issues in oceanographic research from fisheries (Fernandes and Brierley 1999) to measurements of water currents (Stansfield *et al.* 2001).

Jane's currently lists 75 AUVs (Funnell 2001) worldwide, although there may be more model variants of those listed and some, such as the Icelandic *Gavia*, are not listed. The latter is particularly relevant as a new development because it represents one of the increasing number of vehicles currently available to purchase: others include Haliburton's *Autosub*, the Maridan 600, and Simrad's *Hugin* 3000. The latter vehicles have been sold to offshore exploration companies and are now operating commercially as routine platforms for multibeam bathymetry and side-scan sonar surveys (Barton 2002). Not only are they seen as more cost effective but they also obtain better quality data and have shorter turning circles than RVs (reducing survey time).

AUV applications in marine science: the pros

In common with the acoustic applications in the offshore exploration industry, an obvious application of AUVs in marine science is in fisheries acoustics. Fisheries acoustics is a branch of applied biological oceanography aimed at developing and using active hydroacoustic systems for the detection, quantification and qualification of aquatic life. Its application in the assessment of fish stocks and for broader ecosystem studies is well established (MacLennan and Holliday 1996) and becoming ever more significant (Fernandes *et al.* 2002). In the case of many pelagic fish stocks, acoustic survey data are used in assessment models in order to determine population size (Patterson and Melvin 1996). The established technique in fisheries acoustics uses scientific echosounders to transmit sound pulses vertically down into the water at regular intervals (typically 1 s) from a transducer mounted in a survey vessel travelling along defined transects. Returning echo intensities are integrated and converted to species density based on the known acoustic properties of the target (MacLennan and Simmonds 1992). Observations at a single acoustic frequency are sufficient to estimate species density if acoustic data can be ground-truthed with biological samples, for example from nets (McClatchie *et al.* 2000). Density estimates are then converted into areal estimates of species abundance (Simmonds *et al.* 1992).

Fernandes and Brierley (1999) describe how the AUV *Autosub* was used during a survey carried out by the FRV *Scotia* of North Sea herring to address a number of fisheries science objectives as part of the Under Sea-Ice and Pelagic Surveys (USIPS) project. In July 1999 a total of 13 missions were successfully carried out, of which 8 were totally autonomous: this was the first time that a non-military AUV had operated successfully beyond the control range of a support facility. As transducers were mounted on both the dorsal (120 kHz) and ventral (38 kHz) surface of the AUV, a composite echogram, displaying the whole water column including the sea surface, was obtained (Fig. 2). This was the first time that such data were collected unhindered by an umbilical or the effect of a towing support vessel. The advantages of these data are clear from inspection of Figure 2: plankton entrained in an internal wave can be observed almost as a continuum from both images.

Data from the USIPS North Sea missions where the AUV was at a depth of 20 m or greater, were analysed to examine detections of fish schools in the upper dead zone. Surface schools in this zone accounted for less than 1% of the total numbers in the area of the North Sea where *Scotia* conducted the acoustic survey. Further observations of *Autosub* data from the sea surface revealed dive profiles of plunge-diving Northern gannets (*Sula bassana*) and simultaneous data on the distribution of their fish and zooplankton prey (Brierley and Fernandes 2001).

Autosub was also used to examine the effect of fish avoidance of *Scotia*, which was the first vessel to be built to a specification designed to limit noise emission (Mitson 1995). The experiment was conducted in a manner recommended for avoidance studies by Freon and Misund (1999) with the AUV as the independent vessel measuring fish densities ahead of the larger RV on the same transect. In comparison to the 68 m *Scotia*, *Autosub* was small and virtually silent relative to ambient noise levels (Griffiths *et al.* 2001). Avoidance of the AUV by fish was minimal: the vehicle was able to pass very close to a large fish school (Fernandes *et al.* 2000a), causing nothing more than localised school compression that is typical on close approach of a predator (Freon *et al.* 1992). The data collected by *Autosub* and *Scotia* were not significantly different (Fernandes *et al.* 2000a) and it was therefore concluded that that fish did not avoid the quiet RV (Fernandes *et al.* 2000b). A similar experiment was conducted in the Southern Ocean on Antarctic krill using *Autosub* and the RRS James Clark Ross: krill were also found not to significantly avoid the RV (Brierley *et al.* in press).

The USIPS project also undertook deployments of the *Autosub* AUV under Antarctic sea ice, providing the first continuous line transect acoustic surveys of krill in the under ice habitat (Brierley *et al.* 2002). Krill density was found to be elevated under ice, and krill to be concentrated in a narrow band inside the ice covered zone. The unique sampling capabilities of the AUV and scientific echosounder combined

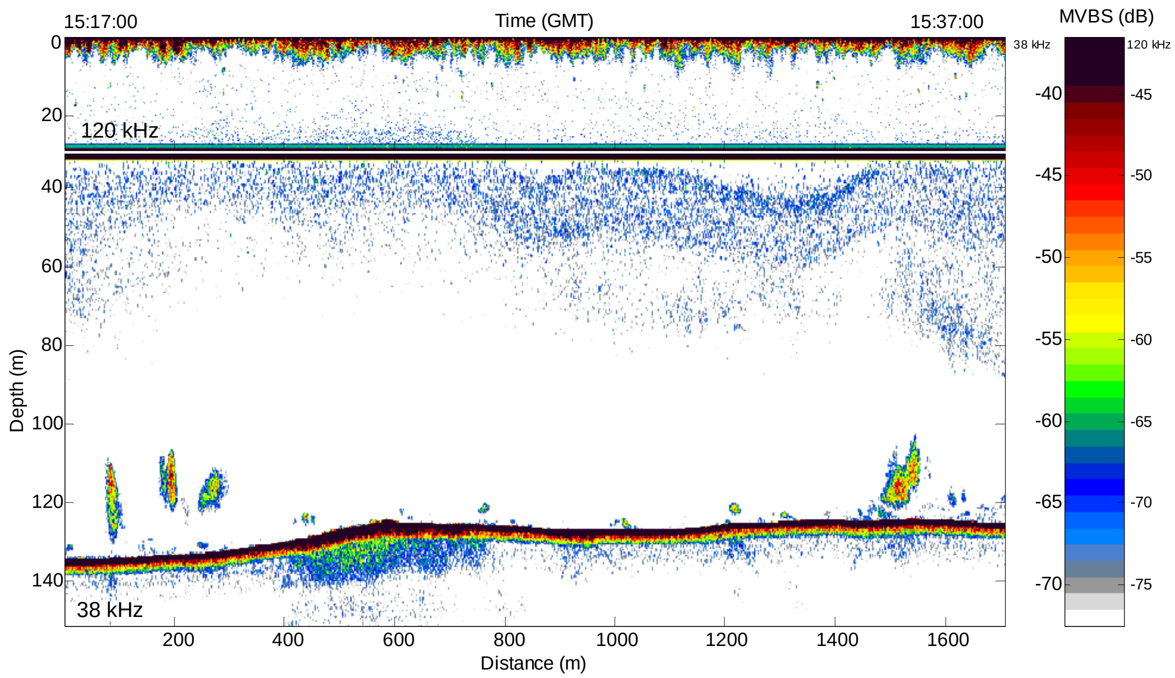

Figure 2. Composite echogram section from data gathered by *Autosub* on 13 July 1999: 120 kHz transducer orientated towards the surface (upper image); 38 kHz towards the bottom (lower image). The four large schools in the lower image near the seabed are almost certainly Atlantic herring (*Clupea harengus*): trawl catches of herring were taken by FRV *Scotia* from similar traces in the vicinity. Internal wave activity is evident from plankton backscatter centred at approximately 40 m depth.

enabled the first quantitative description of the link between krill density and sea-ice cover. Measurements were also made of sea-ice thickness on a scale only previously matched by trials of the military UARS vehicle in the Arctic (Busby 1977). *Autosub* surveyed over 210 km of transects under Antarctic sea-ice (Brierley *et al.* 2002) providing a unique dataset. *Autosub* was also directed beneath large icebergs, providing underwater profiles and, therefore, determining iceberg drafts. In the case of the Antarctic these data could only have been obtained from an AUV because the Antarctic Treaty requires that military vehicles used in there must be available for international inspection (Wadhams 2000).

AUVs are in many respects ideal platforms for acoustic surveys. They can be directed to any depth in the water column and can therefore be positioned such that the species they intend to survey is at sufficient distance so as to have no effect on the natural behaviour but close enough to obtain a good signal to noise ratio. AUVs are extremely quiet (Griffiths *et al.* 2001): *Autosub* passed within 7 m of a school of herring (Fernandes *et al.* 2000a) which have one of the most sensitive auditory capabilities amongst commercially exploited fish (Mitson 1995). They could thus be used for a variety of behavioural observations (studies of vessel avoidance, vertical migration and fishing gear). Incorporation of target tracking and some intelligent software linking this to navigational control could enable AUVs to follow fish or whales to study their behaviour in relation to prey detected by other acoustic devices on board.

Fisheries and plankton acoustic studies could currently benefit from the deep water capabilities of AUVs: transportation of echosounders and transducers to deep water would enable short range, high resolution observations of targets that from the surface become obscured by noise (Watkins and Brierley 1996). This could provide new insights to the composition of deep scattering layers (Magnússon 1996) and other ecologically important zooplankton "hotspots" (Marine Zooplankton Colloquium 2001). CUVNN (1996) recognised that AUVs may be the only practical method of conducting detailed research on deep-water fisheries. Although acoustic surveys do take place for such resources using deep towed vehicles (Kloser 1995), an AUV could be used to gather acoustic data of higher quality, leaving the RV free to concentrate on ground-truth fishing. A similar arrangement could be envisaged for demersal fisheries where deployment of the AUV closer to the seabed would reduce the magnitude of the bottom dead zone (Mitson 1983).

Autosub has also been used for a variety of oceanographic research tasks: Langmuir circulation, turbulence and gas transfer in the upper ocean have been investigated using side-scan sonars, velocity shear and temperature microstructure probes and a free-flooding resonator (Thorpe *et al.* 2002). Aside from access to the sea surface, AUVs are particularly beneficial for such studies of ocean turbulence because of their minimal inherent vibration. The unique ability of AUVs to follow terrain such as the seabed has also been exploited in studies of the spatial variation of turbulence over sandbanks (Voulgaris *et al.* 2001) and high quality hydrographic measurements of deep water (900 m) currents (Stansfield *et al.* 2001).

AUV development: the cons

For the moment, however, there are some major drawbacks with AUVs as sampling platforms. The first is common to many AUV applications – limited range. Even with the most effective power technology the maximum range of *Autosub*, for example, is 940 km. This is about 1/3rd of the distance covered by *Scotia* prior to a half landing during a typical acoustic survey and about 1/6th of a typical 70 m RV. Given that an AUV has been designed to have low drag and efficient propulsion, the range is entirely dependent on the quantity (size) and quality of the power source which currently dominates the vehicle volume. There are however, a number of practical and economical concerns which often make the choice of power source more complex than theoretically possible. Table 1 provides a number of relevant parameters pertinent to the choice of power source on the *Autosub* AUV. The maximum range of 940 km is given by fuel cells although information on the cost of these was unavailable. Of the remaining power sources, the most cost-effective options are rechargeable lithium ion cells. Lithium ion cells are proving to have a much greater cycle life and are more straightforward to maintain than silver zinc cells (which have a slightly longer range). However, either of these would require a significant initial investment and involve some risk in loss of the vehicle before the economic gains could be recouped. For short one-off experiments, such as in the USIPS project, manganese alkaline batteries are the cheapest option, although they are by far, the least cost effective. Invariably AUVs are weight limited, such that, for example, the cheapest rechargeable solution for *Autosub* (the denser sealed lead acid batteries) become too heavy before taking up the available space and therefore limit the range to 150 km. The temperature of the water may also be a significant factor affecting battery performance but this can be offset somewhat by controlling the dissipation of heat by the batteries.

In the last 6 years, the *Autosub* AUV has gone from an expected maximum range of 300 km in 1996 (Griffiths *et al.* 1997), to 750 km today (Table 1). Improvements in compact, long-lasting sources of power continue apace to service the industries of electric vehicles and, in particular, consumer electronics, where it seems inevitable that fuel cells will soon take over many of the jobs that batteries now do (Service 2002). Fuel cells now feature amongst many AUVs (Table 1), although there are no published accounts of any AUV reaching the maximum theoretical distances specified. Alternative (low) power options under development include solar powered AUVs (Ageev *et al.* 1999) and gliders (Simonetti 1998). Semi-submersibles such as the SASS vehicle are powered by diesel engines and, therefore, have much longer ranges: however, these are restricted to the surface and even more subject to the vagaries of weather than RVs.

Currently, a major drawback of using AUVs in fisheries acoustics is the limited ability to identify acoustic targets: AUVs cannot, and are unlikely to ever, catch fish. However, remote identification using acoustic methods have had reasonable success from single frequency echosounders using echotrace classification (Scalabrin *et al.* 1996; Reid 2000; Lawson *et al.* 2001). This success is likely to be built upon by the incorporation of multifrequency echosounders data (Brierley *et al.* 1998; Korneliussen and Ona 2002) and more complex broadband (Simmonds *et al.* 1996) or chirp systems (Barr 2001). The latter may even be able to discriminate between fish sizes.

Research efforts in the field of acoustic species identification are significant, such that by the time a reasonable method is available, the maximum range of AUVs may have been extended to the sort of scale that may be useful for practical acoustic surveying. In the meantime AUV costs are likely to come down (e.g. the *Gavia* AUV retails at approximately €150,000). Sensor miniaturisation is also likely: the USIPS project adapted a rack mounted Simrad EK500 system (Fernandes and Brierley 1999) resulting in a very large instrument housing. An adaptation of more recent echosounder systems would reduce this volume considerably. As AUVs can be guided to any depth, the maximum range of transducers is not an issue, such that higher frequencies (which have smaller transducers) can be used. Smaller cheaper vehicles, such as *Gavia*, may therefore be viable options. As the costs come down multiple vehicles can be used to provide a more synoptic survey and reduce the effects of horizontal migration. Finally, incorporation of 360º multibeam sonars (or two 180º units as available today) would allow AUVs to sample entire water volumes (Gerlotto *et al.* 1999; Mayer *et al.* 2002). At 100 m range this would increase the volume of water surveyed acoustically by a factor of approximately 60 compared to current vertical echosounders. Advancements in data processing, particularly data scrutinisation, are required in this field before this can be achieved effectively.

Other problems associated with AUVs include: their legal position; avoidance collision at the surface; the complexity of operation and maintenance; and the deployment and recovery from RVs in bad weather. The legal status of AUVs is a controversial and as yet uncertain aspect (Brown and Gaskell 1999). Unlike ships they are small and not totally controllable, yet neither are they totally inert, like buoys. Laws on issues such as salvage are evolving along the lines of ship salvage law, but take into account their autonomous nature where, for instance, an apparently "lost" AUV may have surfaced with no systems visibly running as part of its mission. AUVs found in this manner are not fair game for salvors (Brown and Gaskell 1999). AUVs can easily operate beyond the depths of the deepest drafts of commercial oil tankers (~15 m), but nonetheless must surface at some point and may do so in the event of failure. The provision of a forward-looking collision avoidance sonar would be useful in this respect. Such a system would also assist in avoiding underwater objects such as steep (or overhanging) cliffs, oil rigs, fishing nets and shipwrecks. This system would be yet another addition to the vast array of integrated systems onboard a typical AUV. The command, control, maintenance and fault diagnosis of these

Table 1. Comparative battery performance, using the AUV *Autosub* on science missions, with a 600 kg battery pack. Costs include cost of charging system. **1)** Semi fuel cell with a separator membrane which allows for greater concentration of oxidiser but with greater safety issues e.g. *Altex* AUV (Adams 2002). **2)** Fuel Cell without a separator membrane e.g. *Hugin* AUV (Hasvold 2002). **3)** Hydrogen and Oxygen gas fuel cell (Aoki 1997). *****Energy density is a function of the weight of the hydrogen and oxygen source compared with the plant or fuel cell infrastructure weight, figures quoted relate to actual AUV projects with specific energy densities extrapolated up to the capacity of *Autosub*. ******The lower range quoted has been achieved, the upper range is what is expected with development over the next 5 years (see Hasvold 2002). **4)** Limitless so long as maintenance, repair and support is available.

Battery Type	Specific energy/ mass (kJ/kg)	Cost (€)	Range per charge or per pack (km)	Cycle Life	Energy cost per km (€)	Min. no. of cycles cf. Mn Alk energy cost	Total distance for life of pack (km)
Sealed lead acid	110	21000	150	300	0.59	12	45000
Nickel Cadmium	140	60000	190	1500	0.26	24	280000
Nickel hydride	330	134000	430	1500	0.23	26	640000
Silver Zinc	580	254000	750	80	5.31	29	60000
Lithium Ion	470	254000	610	800	0.63	34	490000
Manganese Alkaline	490 @21°C	7000	640	1	14.91	1	640
Fuel Cell[1]	720*		940		Not available		Limitless[4]
Fuel Cell[2]	360-540**		470 -710				Limitless[4]
Fuel Cell[3]	370*		480				Limitless[4]

systems requires the dedicated attention of at least two experienced and highly qualified staff. This will add to the costs of the vehicle which are not included in Table 1. A variety of deployment and recovery methods exist (Stevenson 2002), but these are still weather dependent. *Autosub* has a dedicated gantry system (Fig. 1) which allowed deployment and recovery in the North Sea in wind speeds up to Beaufort 6. Ideally, a deployment system should be weather independent although, if AUV range could be improved they could be deployed from any sheltered location.

AUVs in marine science: a prognosis

In the short term, it seems likely that AUVs will be used on an *ad hoc* basis to provide auxiliary data that would be difficult or impossible for the RV to obtain. This includes the type of continuous measurements made under-ice, in the deep-sea and at the ocean surface. AUVs have been shown to be effective and reliable platforms for fisheries acoustics (Fernandes *et al.* 2000a; Brierley *et al.* 2002). One obvious and immediately feasible application is the acoustic surveying of deep-water fish (see above). For such tasks, RVs will also be required as the deployment platform.

Due to their small size and extremely low self-noise, AUVs could also be employed to study the behaviour of a variety of marine fauna, perhaps even going in search of giant squid. Iwakami *et al.* (2002) have already succeeded in detecting a humpback whale underwater and approaching it within 50 m.

The array of AUVs available is already substantial (Funnell 2001) and there is no doubt that specific tasks will dictate vehicle size, design and payload. Slocum gliders (Simonetti 1998), for example, use variable buoyancy engines and, therefore, have ranges of the order of thousands of km. Although limited in degrees of freedom (the number of directions a vehicle can travel) these currently provide a good option for long range oceanographic measurements with low power requirements (e.g. measurements of temperature and conductivity).

In the medium term, the first step would be to remove the need for an RV as a deployment platform. Other than limitations on range (discussed above) there is no technical reason why an AUV should not be deployed from the shore. At the surface, an AUV can navigate by DGPS very accurately (to within 2m) and should therefore be able to avoid the hazards of any shoreline or harbour. Free from the expense of an RV, marine scientists may then begin to obtain data from AUVs as independent platforms. Examples where this might be useful include small-scale surveys of medium sized bodies of water such as enclosed seas, lochs, or large lakes, and long term hydrographic sections such as the one in the Faroe-Shetland Channel (Turrell *et al.* 1999).

For more general applications, improvements need to be incorporated from technology transferred from other industries, and costs need to be reduced. The pace of development is such, however, that it may be more effective to use AUVs than RVs within the next 5-10 years. Ultimately, a number of small, cheap AUVs could each be equipped with a multifrequency echosounder (for echo integration, species identification, and substrate classification), a 360° multibeam sonar (operating to a range of 500 m, giving a swept area of 0.8 km^2 for each transmission) and hydrographic samplers (CTD and fluorimeter). These could be deployed to measure the abundance and distribution of a wide variety of fish and plankton on a much more regular basis than that achieved today (for less cost), independent of prevailing weather conditions, environment (continental shelf, shallow water, under ice, or the deep sea) and time constraints. These may ultimately provide data of sufficient quantity (sample size) and quality for cost effective monitoring of marine resources.

In the longer term (>15 yrs), perhaps the most significant application of AUVs will be in providing a platform for routine marine data gathering exercises, such as for example, acoustic surveys. Increasing RV costs, reductions in working times, and possible further losses due to bad weather are factors which are just simply incompatible with the mounting requirement for survey data. RVs will perhaps be unable to cope with any increased demand. The price of an AUV is currently at most $1/24^{th}$ of that of an RV to purchase and of the order of $1/35^{th}$ of an RV to run[1]: such discrepancies are likely to increase in future. In a major review of national needs in relation to AUVs, CUVNN (1996) concluded that AUVs with appropriate acoustic sensors could provide better sampling coverage and better resolution in a cost effective way for the assessment of fish stocks in US waters. If and when exactly this happens remains to be seen, but AUVs are emerging as alternative sea-going marine data gathering platforms which currently can be used to supplement RV data, and in future may help to alleviate the demand for certain types of data from increasingly overstretched RV programmes.

[1] Based on estimated costs of the replacement for FRV *Cirolana* of approximately €36 million and a running cost of €22 km^{-1}. *Autosub-2* expected cost approximately €1.5 million and a running cost of €0.63 km^{-1} (based on a long range lithium ion battery – see Table 1).

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