

Autonomous underwater vehicles: future platforms for fisheries acoustics

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Autonomous underwater vehicles (AUVs) are unmanned submersibles that can be pre-programmed to navigate in three dimensions under water. The technological advances required for reliable deployment, mission control, performance, and recovery of AUVs have developed considerably over the past 10 years. Currently, there are several vehicles operating successfully in the offshore industries as well as in the applied and academic oceanographic sciences. This article reviews the application of AUVs to fisheries- and plankton-acoustics research. Specifications of the main AUVs currently in operation are given. Compared to traditional platforms for acoustic instruments, AUVs can sample previously impenetrable environments such as the sea surface, the deep sea, and under-sea ice. Furthermore, AUVs are typically small, 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 utilized in fisheries-acoustics science are given with reference to previous work in the North Sea and Southern Ocean and to potential future applications. Concurrent advances in multi-beam sonar technology and species identification, using multi-frequency and broadband sonars, will further enhance the utility of AUVs for fisheries acoustics. However, before many of the more prospective applications can be accomplished, advances in power-source technology are required to increase the range of operation. The paper ends by considering developments that may turn AUVs from objects sometimes perceived as science fiction into instruments used routinely to gather scientific facts.

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Introduction

The application of fisheries acoustics in the assessment of fish stocks and for broader ecosystem studies is well established (MacLennan and Holliday, 1996). In the case of many pelagic fish stocks, acoustic-survey data are essential inputs to assessment models that determine population size (e.g. Patterson and Melvin, 1996). Learning the lessons from the collapse of the Canadian cod stocks, key proponents of assessment methodology now concede that there is a continued need to invest in survey indices of abundance and that improvement may come from direct technological approaches to fish counting using sonar (Walters and Maguire, 1996).

The established technique in fisheries acoustics uses integrated outputs from scientific echosounders to determine

fish density (MacLennan and Simmonds, 1992). Density estimates are then converted into areal estimates of species abundance (Simmonds *et al.*, 1992). Echosounder transducers are typically mounted on the hull of research vessels (RVs), on drop keels, or in towed bodies, all of which are located several metres below the sea surface. Consequently, approximately 10 m of the upper-water column, the “upper dead zone” (Aglen, 1994), is unsurveyed. A “bottom dead zone” also exists in the order of 1–2 m (Mitson, 1983), increasing in size with increasing distance from the transducer (depth). Many of the demersal fish such as cod, haddock, and whiting inhabit this zone and cannot be detected. Physical restrictions on long-range sound propagation also prevent useful acoustic data being collected from the deep sea, where sensitive fisheries lie (Gordon *et al.*, 1995).

Beyond the fisheries of temperate latitudes, large areas of the polar oceans are either permanently or seasonally ice covered. Despite its sterile appearance, sea ice is a habitat of major ecological importance (Brierley and Thomas, 2002), but sampling limitations inherent with conventional platforms have left the region little known. In open water, Antarctic krill (*Euphausia superba*), a key species in the Southern Ocean, are assessed acoustically (Brierley *et al.*, 1997), but although the ice-covered zone is believed to be a vital habitat for krill (Quetin *et al.*, 1996), until recently little was known of krill abundance there.

In addition to applications in fisheries science, acoustic-sampling techniques are used widely in physical and biological oceanographic research (e.g. acoustic Doppler current profilers (Brierley *et al.*, 1998a) and multiple high-frequency devices (Holliday *et al.*, 1989)). In many of these studies, limitations have been imposed on the portion of the water column that can be probed, either by constraints in the operating depths of the acoustic instruments or the platforms upon which they were mounted, or by the physical propagation of sound through water.

RVs themselves have operating thresholds and are limited by adverse weather conditions. In the longer term, 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 that may limit RV survey time, at least in the European Union, is legislative restriction on working time.

There are, therefore, current limitations on RV capabilities and future concerns regarding their operating time and costs. Yet there is a growing realization that more fishery-independent data are required and fisheries acoustics is developing continually to service this demand (Fernandes *et al.*, 2002a). A similar realization dawned on oceanographers in the early 1990s, when it became clear that conventional sampling devices would not be able to supply data of sufficient quantity and quality to model the influence of the oceans on climate (Griffiths, 1992). The latter review concluded that the way forward lay with autonomous underwater vehicles (AUVs).

AUVs could provide solutions to many of the limitations associated with acoustic sampling from conventional RVs. The objectives of this article are to describe how AUVs can and have been used to overcome some of these limitations, and to suggest future developments which may make AUVs routine platforms for fisheries acoustics.

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 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. Most of the internal space is taken up with the propulsion-energy source and command-and-control instrumentation, which naturally need waterproofing in housings that vary in design according to the operational depth. Most AUVs can operate to 200 m or so, with some operating beyond 5000 m. *Autosub-2* of the UK (Figure 1) is typical of the design of many AUVs. Long-range gliders (Simonetti, 1998) can also be considered as AUVs, although for the purposes of this review they are excluded because of the high power and payload-space requirements of current acoustic instruments; gliders also have restricted horizontal movements which would make systematic surveying problematic.

The first AUVs developed in the late 1960s by the University of Washington (Busby, 1977) for oceanographic research (SPURV) and military exploration under ice (UARS) were successfully trialled in the early 1970s. The 1980s saw a proliferation of AUV technology (Busby, 1990). Notable AUVs in operation included the deep-diving Epaulard of IFREMER, ARCS of ISE Ltd, 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: the MIT Oydyssey vehicles undertaking a number of oceanographic surveys (e.g. Nadis, 1997); Theseus of ISE Ltd completed a 350-km mission to lay a fibre-optic cable under sea ice (Ferguson *et al.*, 1999); and Florida Atlantic University's Ocean Explorer vehicles measured ocean turbulence (Dhanak and Holappa, 1996). In the UK, the NERC started its *Autosub* project in 1987 (McCartney and Collar, 1990) and in 1999 funded a 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).

Funnell (2001), in Jane's Yearbook, currently lists 75 AUVs world-wide, although there may be more model variants of those listed, and some, such as the Icelandic *Gavia*, are not listed. The *Gavia* is particularly relevant as a new development because it represents one of the increasing number of vehicles currently available for purchase: others include Subsea7's *Autosub-2*, the *Maridan 600*, and SIMRAD's *Hugin 3000*. The latter have been sold to offshore-mineral exploration companies and are now operating commercially as routine platforms for multi-beam bathymetry and sidescan-sonar surveys (Barton, 2002).

Fisheries-acoustics applications

The application of AUVs as platforms for fisheries acoustics is similar to their role in offshore-mineral surveying: they provide a stable platform and containment space for acoustic transducers, associated electronics and data storage that can be configured to operate at depth. Of the many vehicles currently available, Table 1 lists some of those that may be appropriate for use in fisheries acoustics.

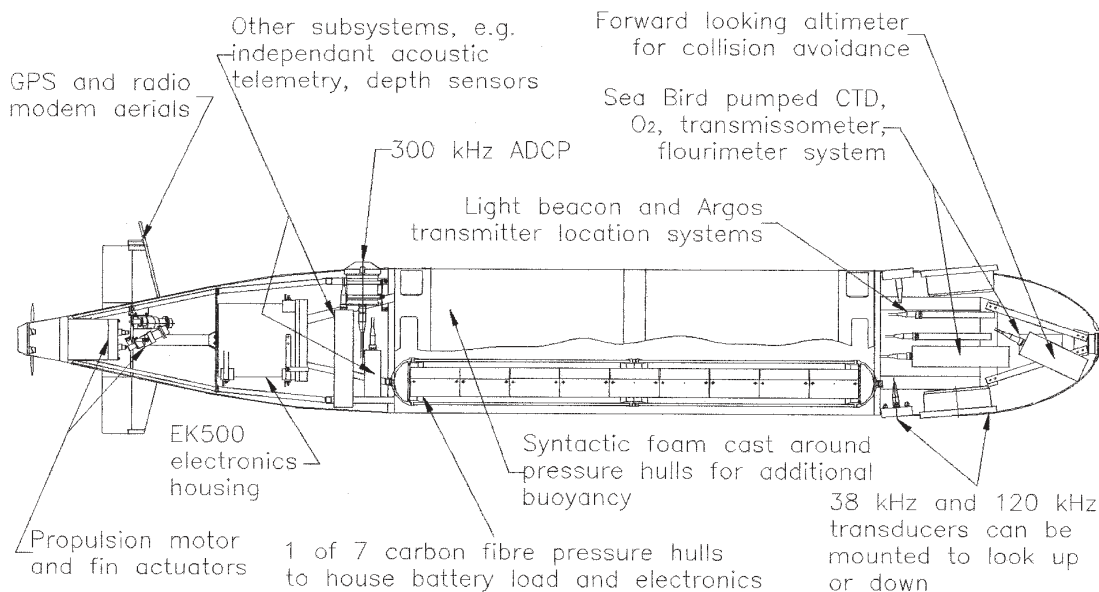


Figure 1. A schematic view of *Autosub-2* with the payload configured for acoustic surveys of aquatic fauna (SIMRAD EK500, scientific, multi-frequency vertical echosounder).

Fernandes and Brierley (1999) describe how the AUV *Autosub-1* was used during a survey carried out by the Fisheries RV *Scotia* of North Sea herring (*Clupea harengus*). *Autosub-1* was used to address a number of fisheries-science objectives as part of the Under-Sea Ice and Pelagic Surveys (USIPS) project. A total of 13 missions were successfully carried out, of which eight were totally autonomous. As transducers were mounted on both the dorsal (120 kHz) and ventral (38 kHz) surfaces of the AUV, a composite echogram, displaying the whole water column including the sea surface, was obtained (Figure 2). This was the first time that such data were collected unhindered by an umbilical or the effect of a towing support vessel.

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-1* 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-1 was also used to examine the effect of fish avoidance of *Scotia*, which was the first vessel to be built to the International Council for the Exploration of the Sea's (ICES) 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. Compared to the 68-m *Scotia*, *Autosub-1* was small and

virtually silent relative to ambient noise levels (Griffiths *et al.*, 2001). The data collected by *Autosub-1* and *Scotia* were not significantly different (Fernandes *et al.*, 2000a) and it was therefore concluded 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-2* and the RRS *James Clark Ross*: no significant avoidance of the RV was detected (Brierley *et al.*, 2003).

The USIPS project also undertook deployments of the *Autosub-2* AUV under Antarctic 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 *per se* to be concentrated in a narrow band just inside the ice-covered zone. 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-2* surveyed over 210 km of transects under Antarctic sea ice (Brierley *et al.*, 2002) providing a unique data set. It was also directed beneath large icebergs, providing underwater profiles and, therefore, determining iceberg drafts.

Future applications

In many respects, AUVs are ideal platforms for acoustic surveys. They can be directed to a variety of depths in the water column and can therefore be positioned at sufficient distance so as not to have an effect on the natural behaviour of the resource they are to survey. They can also approach sufficiently close to enable detection using high-frequency transducers if required. AUVs are extremely quiet (Griffiths *et al.*, 2001): herring have one of the most sensitive

Table 1. AUVs suitable for fish-survey work.

Name	Manufacturer	Size length× diameter (m)	Weight (kg)	Speed (m/s)	Maximum range (km)	Maximum depth (m)	Power source	Sensor payload
ALTEX	Monterey Bay Aquarium Research Institute (MBARI) USA	5.5 × 0.53	—	—	1000	4500	Aluminium oxygen fuel cell	—
ARCS	International Submarine Engineering Ltd (ISE) Canada	6.4 × 0.686	1361	2	235	305	Aluminium oxygen fuel cell	—
AUTOSUB	Southampton Oceanography Centre (SOC) UK	6.8 × 0.9	2200	1.8	750	1600	Manganese alkaline 1° batteries	1, 2, 3, 4, 5
SS7 AUTOSUB	Subsea7 UK	6.8 × 0.9	2400	1.8	800	3000	Lithium ion 2° batteries	3, 4, 6, 8
DELPHINI	Bluefin Robotics Inc, USA and Thales Survey Ltd UK	3.4 × 0.53	400	1.5	111	3000	Silver zinc	—
EXPLORER 5000	International Submarine Engineering Ltd (ISE) Canada	6 × 1.15	3350	2.5	430	5000	Silver zinc 2° batteries	1, 3, 4, 6, 7
GAVIA	Hafmynd Iceland	1.7 × 0.2	50	2	40	2000	Different battery options	1, 2, 6, 8
HUGIN	Kongsberg Simrad A/S Norway C&C Technologies USA	5.35 × 1	—	2	—	3000	Aluminium oxygen fuel cell	1, 3, 4, 5, 6, 7
MARIDAN 600	Maridan A/S Norway	4.5 × 2.0 × 0.6	1700	3.5 max	24 h max	600	Manganese alkaline 1° batteries	3, 4, 6
MUST	Lockheed Martin, Perry Technologies USA	9 long	—	—	24 h max	610	Lead acid	1000 kg, 1500 l
OYDESSY 11c	Massachusetts Institute of Technology (MIT) USA	2.2 × 0.58	200	1.5	66	3000	Silver zinc 2° batteries	—
SEA ORACLE	Bluefin Robotics Inc, USA and Thales Survey Ltd UK	2–6 long	—	1.5	—	3000	Silver zinc upgrade path to fuel cell	3, 4, 6
THESEUS	International Submarine Engineering Ltd (ISE) Canada	10.7 × 1.27	8600	2	780	1000	Silver zinc 2° batteries	550 kg dry 1920 kg wet
TYPHLONUS	Institute of Marine Technology Problems Russia	3.5 × 0.8	900	2	230	2000	—	—
URASHIMA	Japanese Marine Science and Technology Centre (JAMSTEC)	9.7 × 1.5	1350	1.5	300	3500	Lithium ion	6, 8, 9

This list is restricted to vehicles which have either been directed at fisheries surveys (e.g. *Autosub* and *Gavia*) or meet the following criteria considered desirable for the task: range > 100 km; depth > 100 m; sensor payload > 30 kg wet; truly autonomous (i.e. able to run unescorted missions without acoustic tethers or baseline beacons); non-military vehicles. Sensor payload key: 1 = CTD; 2 = ADCP; 3 = sub-bottom profiler; 4 = multi-beam sonar; 5 = scientific echosounder; 6 = sidescan sonar; 7 = magnetometer; 8 = camera; 9 = water sampler.

auditory capabilities among commercially exploited fish (Mitson, 1995), and yet *Autosub-1* passed within 7 m of a school (Fernandes *et al.*, 2000a). AUVs could thus be used for a variety of behavioural observations, e.g., studies of vessel avoidance, vertical migration, and fishing gear. The 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 deepwater capabilities of AUVs: the transportation of echosounders and transducers to deep water would enable short-range, high-resolution observations of targets that from the surface become obscured by

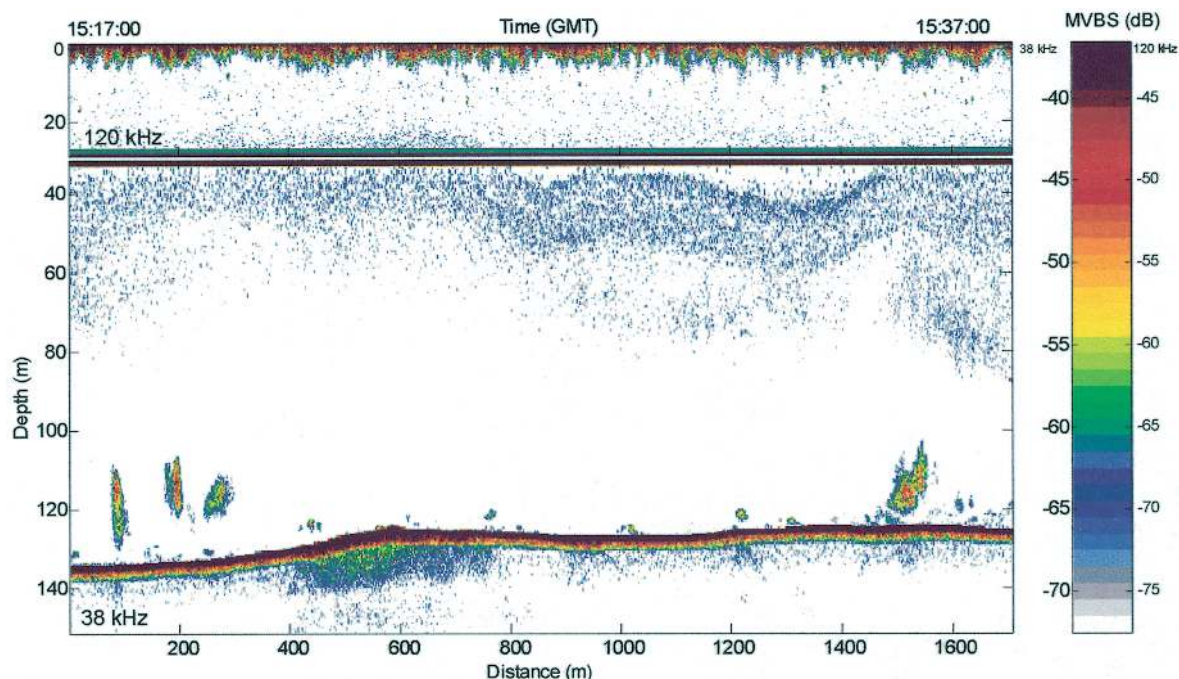


Figure 2. A composite echogram section from data gathered by *Autosub-1* on 13 July 1999: 120 kHz transducer orientated towards the surface (upper image); 38 kHz towards the bottom (lower image). The four large schools in the lower image near the seabed are almost certainly Atlantic herring (*Clupea harengus*): FRV *Scotia* took trawl catches of herring from similar traces in the vicinity.

noise (Watkins and Brierley, 1996). This could provide new insights into the composition of deep-scattering layers (Magnússon, 1996) and ecologically important zooplankton “hotspots” (Marine Zooplankton Colloquium, 2001). CUVNN (1996) recognized that AUVs may be the only practical method of conducting detailed research on deepwater fisheries. Although acoustic surveys do take place for such resources using deep-towed vehicles (Kloser, 1996), an AUV could be used to gather acoustic data of higher quality, leaving the RV free for ground-truth fishing. Furthermore, turning an RV with a vehicle in tow at the end of thousands of metres of wire, takes a long time and is difficult to do accurately, particularly in small areas such as seamounts where many of the deepwater resources lie (Kloser *et al.*, 1996). Surveys of mobile fish populations in such areas will therefore be significantly more efficient with an AUV. Similar arrangements could be envisaged for demersal fisheries, where deployment of an AUV closer to the seabed would reduce the magnitude of the bottom dead zone (Mitson, 1983).

However, perhaps the most significant application of AUVs in the longer term will be in providing a platform for routine acoustic surveys. Mounting RV costs, reductions in working times, and possible further losses due to bad weather are factors that are just incompatible with the increasing requirement for acoustic surveys. RVs will simply be unable to cope with any increased demand. The purchase price of an AUV is currently at the most a 20th that of an RV; running costs are in the order of 1/50th of an

RV (see Table 2). 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.

For the present, however, there are at least two major drawbacks with AUVs as sampling platforms for fisheries acoustics: operational range and target identification. Even with the most effective battery technology the maximum range of *Autosub-1*, for example, is 750 km. This is about one-third of the distance covered by *Scotia* prior to a “half landing” (mid-cruise break) during a typical acoustic survey and about one-sixth of a typical 70-m RV. The range is entirely dependent on the quantity (size) and quality of the power source, which currently dominates the vehicle volume (e.g. Figure 1). There are, however, a number of practical and economical concerns, which often make the choice of power source more complex than theoretically possible. Table 2 provides a number of relevant parameters pertinent to the choice of power source on the *Autosub-1* AUV. Silver–zinc batteries give the maximum range, but the most cost-effective are lithium-ion cells. However, 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

Table 2. Comparative battery performance using the AUV *Autosub* on science missions with a 600-kg battery pack. Costs include cost of charging system.

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	21 000	150	300	0.59	12	45 000
Nickel cadmium	140	60 000	190	1500	0.26	24	280 000
Nickel hydride	330	134 000	430	1500	0.23	26	640 000
Silver zinc	580	254 000	750	80	5.31	29	60 000
Lithium ion	470	254 000	610	800	0.63	34	490 000
Manganese alkaline	490 at 21°C	7000	640	1	14.91	1	640
Fuel cell ^a	720*		940				Limitless ^c
Fuel cell ^b	360–540**		470–710			Not available	Limitless ^c
Fuel cell ^d	370*		480				Limitless ^c

^aSemi-fuel cell with a separator membrane that allows for greater concentration of oxidizer but with greater safety issues, e.g. Altex AUV (Adams, 2002).

^bHydrogen-and-oxygen, gas fuel cell (Aoki and Shimura, 1997). *Energy density is a function of the weight of the hydrogen and oxygen source compared with the plant or fuel cell infrastructure weight. The 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).

^cLimitless so long as maintenance, repair, and support are available.

^dFuel cell without a separator membrane, e.g. *Hugin* AUV (Hasvold, 2002).

Autosub-1, the denser, sealed-lead-acid batteries, becomes too heavy before taking up the available space and is therefore limited to a range of 150 km.

In the past six years, the *Autosub-1* AUV has gone from an expected maximum range of 300 km in 1996 (Griffiths *et al.*, 1997) to 750 km today (Table 2). 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 among 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).

The second major current drawback of using AUVs for fisheries acoustics is the verification of 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 echotracer classification (Scalabrin *et al.*, 1997; Reid 2000; Lawson *et al.*, 2001). This success is likely to be built upon by the incorporation of multi-frequency echosounders (Brierley *et al.*, 1998b; Kloser *et al.*, 2002; 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 could be useful for practical acoustic surveying. In the meantime, AUV costs

are likely to decrease (e.g. the *Gavia* AUV retails at approximately €150 000). Sensor miniaturization would also be advantageous, as the payload space available in AUVs is generally limited. The USIPS project adapted a rack-mounted SIMRAD EK500 system (Fernandes and Brierley, 1999) resulting in a large instrument housing (Figure 1). An adaptation of more recent echosounder systems would reduce this volume considerably. As AUVs can be guided to a variety of depths, the maximum range of transducers is not an issue, such that lower power and 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 could be used to provide a more synoptic survey and reduce the effects of horizontal migration. The vehicles would have to travel at a minimum depth of 15 m to avoid the draft of the largest oil tankers and would benefit from some form of collision-avoidance system that would keep them away from submerged obstacles such as mineral exploration facilities and fishing nets. Some form of cooperation with the appropriate fishing industry would be advantageous, particularly if biological samples are required. Finally, incorporation of 360° multi-beam sonars (or two 180° units as available today) would allow AUVs to sample entire water volumes (Gerlotto *et al.*, 2000; 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. Advances in data processing, particularly data scrutiny, are required in this field before this can be achieved effectively.

AUVs have been shown to be effective and reliable platforms for fisheries acoustics (Fernandes *et al.*, 2000a; Brierley *et al.*, 2002). They are also being used in other

oceanographic disciplines (Fernandes *et al.*, 2002b), where a wide variety of optical, chemical, and acoustic sensors are used (e.g. Griffiths, 2002). Improvements now 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 multi-frequency echosounders for echo integration, species identification, and substrate classification, a 360° multi-beam sonar operating to a range of 500 m, giving a swept area of 0.8 km² for each transmission, and hydrographic samplers (CTD and fluorimeter). Independent of prevailing weather conditions, the environment, i.e. continental shelf, shallow water, under ice, or the deep sea and time constraints, and for less cost, these could be deployed to measure the abundance and distribution of a wide variety of fish and plankton on a more regular basis than that achieved today. Ultimately they may provide data of sufficient quantity (sample size) and quality for the cost-effective monitoring of marine resources.

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