OPEN OCEAN OPERATIONAL EXPERIENCE WITH THE AUTOSUB-1 AUTONOMOUS UNDERWATER VEHICLE

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Abstract
The Autosub-1a autonomous underwater vehicle (AUV) designed, built and operated by the Southampton Oceanography Centre is a medium endurance, multipurpose sensor platform designed for marine science studies of the upper ocean. With a specified range of 250 km, operating at 3.8 kt, and a diving depth capability of 500 m the vehicle has completed 179 engineering and science missions in UK coastal waters, off the east coast of Florida and off Bermuda. This paper focuses on three key areas particularly important to AUVs operating on long missions in the deep or open ocean: the predictability of the primary cell energy supply, particularly its predictability; buoyancy changes in a vehicle without active buoyancy control and scientific sensor performance – the raison d'être for the vehicle. We draw upon the methods, observations and results from the 1998 Autonomous Vehicle Validation Experiment (AVVEX) when Autosub-1a operated off Bermuda in August-September 1998.

1. Introduction
The Autosub-1 autonomous underwater vehicle (AUV) designed, built and operated by the Southampton Oceanography Centre is a medium endurance, multipurpose sensor platform designed for marine science studies of the upper ocean, Millard et al. (1998). Autosub-1 is a relatively large vehicle at 6.8 m long and 0.9 m in diameter with a battery payload capacity of 300 kg and a sensor capacity of 1000 litres or 100 kg weight in water, whichever is less, Figure 1. The vehicle uses a space-frame construction to provide physical modularity with a main pressure vessel of filament-wound glass fibre reinforced plastic (with an internal volume of 383 litres), Stevenson et al. (1998). This pressure vessel, which only holds the batteries and power management system, limits the operating depth to 500 m. Most other vehicle systems are in anodised aluminium or titanium pressure vessels rated to 6000 m. Upgrading the vehicle depth rating is thus a matter of upgrading the main pressure vessel and the foam buoyancy modules. An event-driven, distributed networked architecture is employed for the vehicle control system, including mission management, based on LonWorks modules and the LonTalk protocol, McPhail and Pebody (1998). Both secondary (lead-acid) and primary (manganese alkaline) batteries have been used to power the vehicle. Using sealed lead-acid batteries the maximum mission endurance is 10 hours, whereas with the primary battery the vehicle has demonstrated an endurance of over 50 hours, covering 263 km.

The vehicle was first launched within the confines of Empress Dock, Southampton, in May 1996, for a series of engineering trials as an ROV and later as an AUV. In July and November 1996 two engineering trial campaigns were successfully completed at Portland Harbour, UK, an enclosed area of some 5 km² with water depths of 15 m. Box survey missions of up to 30 km were made and we demonstrated a beach-approach terrain-following mission at an altitude of 2.5 m, Griffiths et al. (1997), Millard et al. (1997). The vehicle acceptance trials took place near Oban, Scotland in April 1998 with a campaign that included box surveys, depth and terrain-following undulating sections down to 195 m, Millard et al.
(1998). During these trials we also demonstrated the vehicle’s ability to leave a quiet harbour autonomously, Griffiths et al. (1998a).

Autosub-1’s first open ocean experience was off the east coast of Florida in December 1997, operating at the edge of the Florida Current, Griffiths et al. (1998b). The missions comprised terrain-following and 'lawnmower' pattern sections with the vehicle carrying ocean environment sensors including three CTDs, a pH probe and a Doppler current profiler. The longest mission covered 110 km in a lawnmower pattern of 64 legs of 1.3 km east-west sections, with short north-south joining sections across the Florida shelf break.

In August-September 1998 Autosub-1 completed 11 missions in oceanic waters off Bermuda in the Autonomous Vehicle Validation Experiment (AVVEX). During AVVEX, the vehicle achieved its deepest dive to date (504 m) and its longest range (263 km). More recently (April 1999) the vehicle has completed four weeks of trials with new sensors (forward and side-looking sidescan sonars, turbulence probes and a fisheries echo sounder) as well as testing a new launch and recovery gantry, Figure 2. These trials were in preparation for an 18-month programme of science missions in UK waters, the Mediterranean and the Southern Ocean.

To date, Autosub-1 has completed 179 missions, enabling the development team to gather a wealth of operational experience in a number of areas, including:

- Reliability of mechanical, electrical and electronic systems; in-service maintenance requirements; software maintenance and change control;
- Maintaining vehicle mission integrity given unreliable sensor data;
- Confirmation (or otherwise) of theoretical performance against practical results for vehicle and sensor systems;
- Mission programming techniques and trapping human errors in mission specification;
- Quirks of (D)GPS navigation of a surfaced AUV when leaving harbour, in coastal waters and in the open ocean;
- Sensor interfaces (electrical, data and mechanical) for commercial off the shelf and experimental sensors;
- Power and endurance calculations for the main vehicle battery pack when using temperature and load-sensitive primary batteries;
- Collision avoidance; acoustic and radio telemetry; sub-surface navigation using magnetic heading sensors and Doppler velocity log;
- Handling for launch and recovery from a range of vessels; buoyancy control;
- Data dissemination;
- The uncertain framework in national and international law for AUV operations.

In this paper, we focus on three of these areas particularly important for AUVs operating on long missions in the deep or open ocean: energy supply, buoyancy change and the performance of the environmental sensors. We draw upon the methods, observations and results from the 1998 Autonomous Vehicle Validation Experiment (AVVEX).

2. Autonomous Vehicle Validation Experiment - AVVEX '98

AVVEX was a collaborative project between the Southampton Oceanography Centre (SOC) and the Bermuda Biological Station for Research (BBSR) with associated investigators from the University of
California at Santa Barbara (UCSB), Florida Atlantic University (FAU) and the University of South Florida (USF). The project, sponsored by the US National Science Foundation and the UK Natural Environment Research Council, as part of the NERC Autosub Science Missions thematic programme technology upgrade trials, had a number of objectives:

- Demonstrate ease of integration of ‘commercial off the shelf (COTS)’ and experimental sensors;
- Demonstrate gathering of multidisciplinary data from an AUV in a number of survey modes;
- Demonstrate added value of AUV spatial survey to on-station data;
- Demonstrate the use of a medium endurance AUV as an adjunct to time series upper ocean data collected from the Bermuda Testbed Mooring;
- Verify that such operations could become routine and cost-effective.

AVVEX operations occupied two periods on RV Weatherbird II, from 21 - 24 August and 4 - 6 September. Ten missions were completed during the first period, focusing on handling trials and process study experiments with missions of up to 24 km in length and to 400 m, carrying FAU’s turbulence probe and USF’s pH sensor. The second period was devoted to one mission, the technical objectives of which were to demonstrate autonomy over 50 hours, covering at least 250 km and profiles to 400 m. The objective was successfully met on mission 145, which covered 263 km with a maximum depth of 504 m. An annotated depth profile of this mission is shown in Figure 3.

AVVEX provided an excellent opportunity to obtain open ocean experience with the AUV operating in a number of modes; especially profiling and constant depth transects. We gained valuable experience of handling the vehicle on a medium sized (102’) research vessel, with no specialised handling equipment, in weather conditions that included the far field of hurricanes Bonnie and Daniel.

3. Energy supply for medium-endurance AUV missions

Inexpensive energy sources remain a Holy Grail for AUV operators. For missions up to 10 hours Autosub-1 can run on lead-acid batteries (seven 12 Volt 85 Ah sealed gel units), providing an efficient, low cost, easily recharged power supply. However, for missions up to 50 hours endurance our choice was not so obvious. Nickel Cadmium cells have a low gravimetric energy density (typically 144 kJ/kg) and require special handling for disposal or recycling. Lithium secondary cells remain prohibitively expensive capital purchases for the size of pack needed for Autosub-1. Lithium-Ion cells’ gravimetric energy density at 360-430 kJ/kg is only mediocre, but Lithium-Polymer is more attractive at 550-610 kJ/kg, Vincent (1999). While Silver-Zinc secondary cells are used in some AUVs their life-cycle economics warrants careful evaluation. Some low rate, high capacity silver-zinc cells have gravimetric energy densities approaching 720 kJ/kg and a practical life of at least 20 cycles. To an end-user in the UK, the cost of energy from such a source (assuming 20 cycles) not allowing for the specialised charging and maintenance procedures is approximately $30/MJ. This figure does not allow for any residual scrap value for the cells. While we would not find such a cost prohibitive, it is predicated on achieving 20 cycles within the life span of the cell.

Without a programme of work calling for 20+ missions of 250 km we chose to use primary manganese alkaline cells. The battery pack was made up from 30 parallel sub-packs of 72 ‘D’ cells in series, 2160 in all. Although our use of primary cells avoided a number of uncertainties present when using secondary cells, such as initial state, charge retention and balancing, predicting the total energy capacity available during a real mission was still not straightforward. Cell temperature and discharge rates have profound effects on capacity.

Data sheets gave the energy capacity per cell at approximately 66kJ at 20°C and a 10 Ω load. In contrast, our measurements, at a discharge rate equal to the maximum AUV load, showed that the energy available
per 'D' cell was lower, but increased with cell temperature, from 49 kJ per cell at 27°C to 58 kJ at 45°C. However, ambient temperature alone cannot be used in the capacity-predicting model. During discharge, the cells warm up. A small part of the temperature rise is due to resistive ($I^2R$) losses but most is due to the generation of heat as a by-product of the electrochemical reaction.

At a discharge current of 0.33 A, the average internal resistance of a cell was found to be 0.15 Ω giving an overall power loss of some 35 W. However, this relatively low power loss did not account for the observed temperature rise of 30° over the length of the 110km mission described in the introduction. In order to estimate the heat output of the exothermic electro-chemical first, we assumed each cell to be 100% efficient at close to zero current discharge. Second, by extrapolating the manufacturer's energy data back to zero discharge the total chemical energy in a new cell could be estimated. Subtracting the actual electrical energy extracted from the total initial energy gave an indication of the heat produced. For a 0.33A discharge in a 2160 cell pack, this yielded a total of some 460 W, including the 35 W resistive losses.

Therefore, the thermal management of the alkaline battery pack assembly within the vehicle is a compromise between the need to limit heat dissipation - in order to maximise energy capacity - and the need to stay below a safe temperature for the cells - to avoid internal pressure build-up caused by gas formation internal to the cell. In practice, the battery pack is also thermally coupled to the exterior ocean environment, whose temperature varies with depth. On mission 145, for example, the external temperature fell from 28.5°C at the surface to 18°C at 500 m.

Each of the 72-cell packs is of a trapezoidal shape, with two tubular channels near the centre. The packs lie on PTFE-coated aluminium trays with aluminium heat transfer rods threaded through the channels in the packs. In turn the trays and rods are thermally coupled to the titanium end-domes of the battery pressure vessel. Several temperature sensors are set within the battery assembly and thermal fuses, set at 70°C, are fitted to each pack (in addition to electrical fuses).

The second factor is the reduction of energy capacity with increasing current drain per cell, a reduction that changes with cell temperature. Three current drain states dominated mission 145: hotel load only (94 W); low power propulsion (224 W plus hotel); cruise propulsion (522 W plus hotel). These periods totalled 3.16 hours, 17 hours and 33.3 hours respectively, a total energy consumption of 94.38 MJ, the voltage discharge curve with time is shown in Figure 4. We estimated the remaining energy in the pack at between 11 and 24 MJ or sufficient for 4 - 10 hours at maximum load. The energy cost for this mission was $43/MJ.

4. Buoyancy, pitch and roll performance
4.1 Buoyancy changes under pressure

Autosub-1 consists of a free-flooding aluminium space-frame structure clad with glass fibre panels. Within the space-frame are metal pressure tubes for sensors and system units, actuators etc., the large (383 litre internal volume) filament wound glass fibre pressure vessel for the battery pack and a number of closed-cell foam buoyancy modules. The vehicle does not use an active buoyancy control system. At the surface, the ballast is manually adjusted to provide positive buoyancy of about 120 N; an important safety feature. This positive buoyancy results in the vehicle adopting a nose-down attitude when travelling at a fixed depth. Composite data from missions 136 and 145 showed that near the surface, the pitch angle was -2.1 to -2.2° whereas at 504 m the pitch angle varied between -1.29 and -1.40°, indicating an overall loss of vehicle buoyancy, Figure 5(a).

This is to be expected since the foam buoyancy modules and the GFRP pressure vessel compress with pressure and contract with falling temperature. The approximate compressibility of the foam was
measured during the proof testing of the GFRP pressure vessel and the foam blocks. This was done by measuring the volume of water needed to pressurise the components (in practice, measuring the volume of water drained from the test vessel while de-pressurising). The foam buoyancy blocks are of co-polymer cross-linked material rated to a working depth of 500 m with a measured bulk modulus of 624 Nmm\(^{-2}\) compared with a data sheet value of 495 Nmm\(^{-2}\). The pressure vessel is 500 mm outside diameter, 1500 mm long had a measured bulk modulus of 1270 Nmm\(^{-2}\) compared with an estimated 1540 Nmm\(^{-2}\) (the estimate ignores the compression of the titanium end domes). For the pressures and temperature range encountered, the volume change from the compression of the foam and the pressure vessel were approximately 6 times greater than that from contraction due to temperature. Given that the volume of foam was double the displacement of the pressure vessel and had a lower bulk modulus, it was the foam that dominated the change in buoyancy, Figure 5b.

Summing all these effects for the vehicle as used in Bermuda, the estimated overall change in displacement over 500 m depth and 10\(^{6}\) temperature change was 12.8 litres. But this has to be offset by the increase in seawater density due to increasing pressure, lower temperature and slightly higher salinity at depth. The net effect is an estimated loss of vehicle displacement of 2.9 litres. Assuming small changes in pitch angle are proportional to the changes in net buoyancy (in this case 120 N), this suggests the pitch angle should reduce from the initial 2.2° on the surface to 1.7° at 500 m depth. However, Figure 5a shows a recorded minimum pitch value of 1.4°. The 0.3° difference between the observed and predicted change may be due to experimental error in measuring the bulk moduli of the foam and pressure vessel. This measurement relied on calculating how much the water compressed and the test vessel expanded under the test pressure and subtracting this volume from the total volume of water drained during depressurisation. But, to account for a difference of 0.3°, the true bulk moduli would need to be 10% lower than the measured values, which were already lower than estimated at the design stage. Alternatively, the measured bulk moduli may be reasonably accurate and additional compression occurred in other parts of the vehicle. For instance, there was 37 kg of cabling (including end connectors) that may have contributed to changes in displacement.

The results illustrate the difficulty in designing an AUV with fixed buoyancy that is, of necessity, low, in order for the vehicle to dive. With the depth specification of 2500 m for Autosub-2 these issues will need careful attention to ensure that the safety of the vehicle and its controllability are not compromised.

4.2 Short-term pitch and roll variations

The short-term pitch and roll stability of an AUV is important for a number of sensors, particularly the sidescan and bathymetric sonars that may feature as future Autosub payloads. Unfortunately, the engineering data logger experienced congestion during AVVEX, resulting in some missing data, which has hampered our ability to compute spectra of pitch and roll. Nevertheless, some measure of the vehicle short-term stability can be obtained from the histograms for mission 136 shown in Figure 6. At 5 m depth the vehicle was clearly influenced by the long-period swell (height ~ 1.5 m) and the local sea (height ~ 0.5 m). While, at 255 m, the figures of 0.42° rms pitch and 0.18° rms roll more closely represent the inherent stability of the vehicle.

5. Oceanographic sensor performance

The only use for an ocean science AUV is as a platform for sensors. If the sensor data is degraded because of interaction between the sensor and the vehicle, then the usefulness of the data, and the platform, will both be reduced? Degradation in data quality may also occur because of straightforward fouling, blocking or leaks. Sensors that needed physical contact with the seawater were handled in one of three ways:
1. A pumped supply of seawater from a port on the vehicle surface near the nose was fed to sensors housed within the vehicle (e.g. Seabird CTD, fluorometer, dissolved oxygen).
2. The sensors were placed towards the rear of the vehicle with the active element protruding through the vehicle cladding (e.g. FSI CTD, pH probe, dissolved nitrate).
3. In the special case of the FAU turbulence and temperature microstructure probe it was fitted to the very nose of the vehicle to ensure the optimum exposure to the free-stream flow.

In order to minimise possible sensor damage and to maximise propulsion efficiency through maintaining low drag, option 1 was generally preferred. However, our experience on AVVEX with the Seabird CTD sensors caused us to rethink the balance of advantages.

The upper ocean off Bermuda exhibits a strong seasonal thermocline in the upper 300 m, with the surface waters over 10°C warmer than at 300 m, Figure 7(a). Four successive profiles are shown in this diagram, down-up-down-up, as in Figure 7(c). The initial impression is that the temperature measurements were reasonably repeatable and the slight differences might be ascribed to kilometre-scale horizontal oceanic variability. However, in the salinity profiles, Figure 7(b), the four profiles were clustered as two groups of two, which upon investigation proved to be down&down and up&up. Furthermore, the difference between the two clusters was related to the temperature gradient; compare the difference at 75 m to that at 300 m. The temperature-salinity diagram, Figure 7(d) clearly illustrates this down-up profile hysteresis. Such an artefact makes the data of limited use to physical oceanographers. Why was the hysteresis so large?

Figure 7(e) shows a close-up of the nose of Autosub-1 with the CTD sensor arrangement on AVVEX. The 12 mm o/d, 250 mm long plastic tube shown as 'A' was coupled to the inlet on the vehicle nose when in actual use. Measurements of the CTD pump flow rate after this mission showed 2 gram/second rather than the design rate of 5 gram/second. A simple heat flow calculation showed that at this low flow rate, an estimated warming or cooling of the sampled water would occur of 0.12°C per degree of temperature difference between the trapped water within the vehicle nose and the water flowing through the sampling tube. When the vehicle transits through the thermocline, the difference between the internal and external temperature was a maximum, hence the offset in salinity.

The Seabird CTD sensors are now fitted externally, to the side of the nose, Figures 7(f&g), where their exposure should result in improved data quality, but at added risk of damage. More complex solutions, such as maintaining the interior sensor placement and surrounding the inlet tube with a larger diameter passively ducted or pumped sleeve of external water was not thought worthwhile.

6. Discussion

Between May 1996 and September 1998 the Autosub-1 graduated from being a tethered ROV under test in a dock to being a well-proven AUV with ocean-going experience on both sides of the Atlantic. In keeping with the ocean science primary mission of the vehicle, most of the mechanical, electrical and software components have remained undisturbed since the early trials. This stability in the basic systems has resulted in a reliable vehicle, enabling trials time to be devoted to proving the mission, science data gathering and engineering capabilities.

An affordable efficient energy supply remains elusive. Manganese alkaline primary cells are, in our opinion, a sensible interim solution. Familiarity, however, conceals important constraints upon their performance. In this paper we have shown that one shortcoming - the heat from the exothermic electrochemical reaction reducing the energy available at high loads - can be used to provide a useful increase in the cell capacity. Deeper diving versions of Autosub-1 will need to pay careful attention to the compressibility of the buoyancy materials as the results shown here suggest that data sheet values may
differ from actual values for this critical parameter. Finally, the performance of some oceanographic sensors may be adversely affected if positioned on an AUV without proper regard to the special factors of the novel sensor environment. Further experience, under the critical eye of oceanographers, will undoubtedly solve these sensor issues.

Acknowledgements
We thank the master and crew of RV Weatherbird II and the shore team at the Bermuda Biological Station for Research for their assistance during AVVEX.

References


Figure 1 Schematic of the Autosub-1 AUV showing the mechanical construction of the vehicle and a typical placement of the major system components and science sensors. Because of the flexibility offered by the space-frame construction sensor and vehicle modules may not always be located in the positions shown.

Figure 2 Nearing the end of a recovery, Oban April 1999. The purpose-designed gantry eases several of the problems inherent in handling the 6.8 m long, 1.7 tonne vehicle. The rotatable carrier houses two winches to minimise the pendulum length during deployment and recovery, while the carrier travels along a telescopic 'T' beam to provide the necessary separation between the vehicle and the ship's stern.
Figure 3 Vehicle depth over 53 hours of mission 145, Bermuda 1998 navigating a box survey around the position of Hydrostation 'S' (32° 10' N 64° 30' W). The mission comprised 43 dives, as follows:

A) transit from near shore to the start of the survey at a depth of 20 m.
B) dive to 504 m, then a horizontal transit at this depth for 7 km.
C) short transit at 20 m then surface for GPS fix.
D) three profiles between 5 and 400 m (nominal), each profile cycle occupying 4 km, or 12 km between surfacings.
E) surface for GPS fix and rendezvous with RV Weatherbird II for CTD cast.
F) as D for 36 km.
G) as E, but extended due to the GPS receiver entering a full 'sky search' mode; while the vehicle was on the surface the opportunity was taken to alter the dive angles over the UHF radio modem so that a depth of 400 m was actually achieved on each profile.
H) the remainder of the mission comprised similar 12 km and 36 km sections with rendezvous for CTD intercomparisons indicated by the extended surfacings (with the GPS receiver subsequently behaving correctly).

Figure 4 The voltage decay curve for the manganese alkaline battery pack on Mission 145. The capacity of these primary cells depends on current drain and cell temperature. Surface water temperature was 28 - 28.5°C and the voltage decay was near the dotted (green) curve (laboratory measurements at 27°C), but the usable capacity increased as the pack warmed up during discharge, with a decay curve more appropriate to a mean battery temperature of at least 45°C, solid (red) curve.
Figure 5 Mean pitch (a) and roll (b) data at constant depths observed during mission 136, August 1998. The pitch figure also includes two data points (at 20 and 504 m) from mission 145, as the vehicle was trimmed differently for roll between these two missions, it was not possible to compare the roll data directly. Error bars represent 95% error of the mean. (c) Compression of the Autosub GFRP Pressure Vessel and the 600 m rated foam.
Figure 6 Pitch variation histograms at 5 m (a) and 255 m (b) and roll at 5 m (c) and 255 m (d), showing the increased variance near the surface under the influence of waves. The swell was approximately 1.5 m with a local sea of about 0.5 m also present.
Figure 7  Temperature (a) and salinity (b) from the Seabird CTD for profiles 9-12 of mission 143 off Bermuda, 23-8-1998 for the profiles shown in (c). The temperature-salinity diagram (d) shows the profiles to be paired - the two up profiles being very similar, but offset compared to the two down profiles. Photograph (e) shows the sensor placement for the mission. To reduce the hysteresis in the up-down profiles the sensors have been mounted external to the vehicle fairing (f), with a close-up in (g).