Autosub6000: A Deep Diving Long Range AUV

Stephen McPhail

Underwater Systems Laboratory, National Marine Facilities Division
National Oceanography Centre, Southampton
European Way, Southampton, SO14 3ZH, UK.
Tel: +44-2380596370, Fax: +44-596149, E-mail: sdm@noc.soton.ac.uk

Abstract

With an ultimate range up to 1000 km, a maximum operating depth of 6000 m, and a generous payload capacity, Autosub6000 is well placed to become one of the world's most capable deep diving Autonomous Underwater Vehicles (AUVs). Recently, Autosub6000 successfully completed its first deep water engineering trials, and in September 2008, fitted with a multibeam sonar, will carry out its first science missions. This paper will describe how we are tackling the design issues that specifically affect a deep diving AUV which must be capable of operating with true autonomy, independently of the mother ship, namely: carrying adequate energy for long endurance and range, coping with varying buoyancy, and maintaining accurate navigation throughout missions lasting up to several days. Results from the recent engineering trails are presented, and future missions and development plans are discussed.

Keywords:

AUV, Robotics, Navigation, Lithium Polymer Battery, Deep Ocean Research.

Introduction

There are several scientific survey AUVs now either operational or in advanced stages of development. For example, the WHOI's Autonomous Benthic Explorer (ABE) has been operational for over ten years [1], carrying out pioneering work in high resolution mapping of mid ocean ridge environments and tracing of hydrothermal plumes. This is soon to be replaced by the 4500m rated SENTRY AUV. Hydroid, with the 6000m rated REMUS 6000, MBARI, with the Seafloor Mapping AUV [2], Altium technologies, with BLUEFIN-21, and International Submarine Engineering, with its Explorer class AUVs [3], all offer AUVs with deep sea science survey capabilities However, the field is still in its youth and (with the exception of ABE), and there is relatively little published literature on the science results of deep AUV missions beyond 3000m deep.

One of main distinguishing characteristics of the Autosub AUV programme, since its conception and first trials in 1996, is that we have emphasised the "Auto" part of its name. From the early days of the program, we have placed great importance upon freeing the mother support ship to carry out other operations, routinely operating the vehicle "over the horizon", beyond communication or tracking range. Extreme examples of this were the Arctic and Antarctic under ice missions (during the UK, Natural Environmental Research Council funded Autosub Under Ice programme), illustrated by 24 hour missions under sea ice, North East Greenland [4], and a 30 km run under an Antarctic ice shelf [5]. In both of these missions the AUV operated well beyond any communications range, or hope of rescue if anything went wrong. For these under ice and other science missions, we developed the control, collision avoidance and navigation systems for the AUV, and gained experience of operating an AUV in extreme environments [6].

For Autosub6000, this philosophy is continued. Ocean class research ship-time is expensive, and should be used effectively. For example, while the AUV is carrying out a high resolution sonar survey, we may wish to make use of the mother ship for taking seabed sediment cores, or for carrying out a wide area multibeam bathymetric survey. These activities may take up to several days, and hence the AUV should be capable of operating unsupervised for long periods.

To achieve the required operating duration and range (particularly when we consider that a deep diving AUV will take several hours to descend to and ascend from its operating depth), we will need to consider carefully the energy storage technology. Another potential issue is the expected buoyancy variation of the AUV as it descends. Unmitigated, this could cause an increase in the effective hydrodynamic drag, and hence decrease the useful range of the AUV.

Unassisted navigation of a deep diving AUV is another challenge. An AUV fitted with a multibeam sonar is capable of bathymetric surveying at a resolution 1 to 5 m (depending on the AUV flying altitude). The value of this data will be decreased if the AUV is not positioned in absolute coordinates with corresponding accuracy, particularly if the AUV is being used to identify interesting seabed features for later, more detailed, investigation by itself or another vehicle (for example a Remotely Operated Vehicle).

Hence there are three issues for an AUV which are *specific* to the *deep* diving and *useful autonomy*:

- Energy storage at high ambient pressures.
- Accurate autonomous positioning of the vehicle throughout its mission.
- Buoyancy change due to compressibility effects.

The paper describes how we are dealing with these issues at a design level, reports on the results of the first Autosub6000 engineering trials, and looks towards the future and more advanced approaches to autonomous navigation.

Approach and Methods

Mechanical Design of Autosub6000

With the important exception of the central cylindrical section of the AUV, which houses the batteries and provides the majority of the vehicle buoyancy, the design of the Autosub6000 AUV is almost identical to that of Autosub3, which is described elsewhere [7]. The free flooded tail section contains the control, navigation , data handling and communications systems, with the nose section substantially free for science payload (Figure 1).

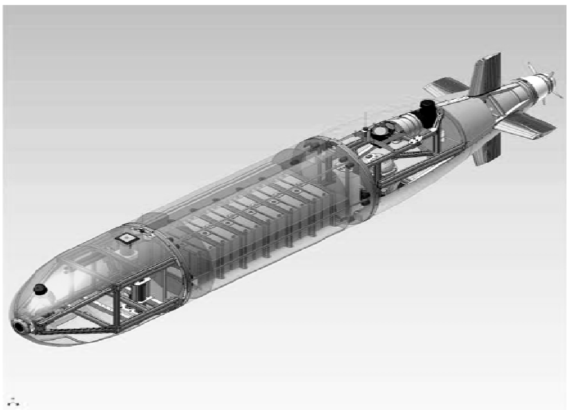

Figure 1. The mechanical arrangement of Autosub6000. Whereas the tail section is mostly filled up with navigation and control systems, the 1.5 long nose is free for science payload.

Autosub6000 is 5.5 m long, with a 2.8 m^3 displacement and a 6000 m depth rating. The main difference between it, and the 1600 m depth rated Autosub3 is in the centre section. Whereas the Autosub3 uses 7, 3 m long carbon fibre pressure cases, 4 of which contain up to 600 kg of primary manganese alkaline cells, Autosub6000 uses a completely different approach. The centre section contains no pressure cases, it is essentially a cylinder of syntactic foam (Emerson and Cuming, EL34 – density 580 kg m^{-3}), with slots cut out for up to 12 batteries.

Energy Storage

Autosub6000 combines a deep depth capability with long range. We achieved these (usually mutually exclusive) characteristics by developing a pressure balanced lithium polymer battery technology, eliminating the need for expensive and bulky pressure resistant housings. Using our in-house deep pressure facilities (up to 68 Mega Pascal), we have carried out extensive pressure cycle testing of the batteries (Figure 2). This approach was first pioneered for use in AUVs by Bluefin robotics [8].

Within the each battery box are 405 Kokam Lithium Polymer cells, storing a total of 16.2 M joule (4.5 kW hr) of energy at a nominal 57 volts, at up to 18 Amperes discharge rate. The batteries are protected against over charge, over discharge, and over current, though fail safe, redundant circuitry. Each battery is monitored via an I^2C bus for currents, voltages , temperature, pressure compensating oil level, and leaks. The batteries weigh 44 kg in air (22 kg in seawater). Dimensions are 569 x 421 x 135 mm.

As the charge monitoring and control are integrated into the battery, charging is relatively simple, only requiring a standard 1.2 kW power supply with current limit operation for each battery.

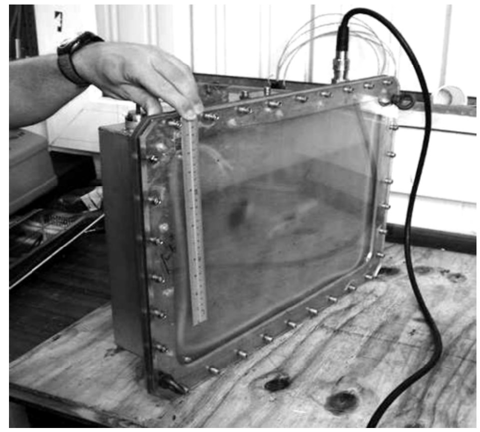

Figure 2. A Pressure balanced battery.

At present, Autosub6000 is fitted with 5 pressure balanced batteries, giving, with a multibeam sensor payload (100 W power), an autonomy of 36 hours and a range of 230 km. There is capacity in the vehicle to increase this to 12 batteries with a proportional increase in range and endurance (longer ranges are possible at slower operating speeds).

Autosub is propelled by a direct drive brushless d.c. motor, and two bladed propeller.

Navigation, communications and Tracking

For dead reckoned navigation, the AUV relies on a 300 kHz Teledyne RDI Workhorse Acoustic Doppler Current Profiler (ADCP) which measures the vehicle velocity relative to the seabed (when within the 220 m bottom tracking range), and an Oceano Ixsea PHINS, Fibre Optic Gyro (FOG) based Inertial Navigation System (INS). These are housed together in a titanium pressure case (Figure 3). Our own and other operators [9] experience with similar systems deployed on AUVs, indicate that when calibrated, the drift rate of this system is of the order of 5 m per hour.

There remain two problems for the accurate navigation of a truly autonomous deep diving AUV:

- Providing the positioning of the AUV after its initial descent to the seafloor without bottom tracking with the ADCP (the initial position problem).
- Controlling the growth of navigation error for long missions hours (the drift problem).

Both of these problems could be tackled by the use of a seabed moored acoustic transponder network. However this approach can be expensive in ship time. It has been reported [10] that to deploy, position, and recover 5 transponders at 4800 m water depth, for acoustic navigation of the ISIS ROV within a square box of only 1 km side, took a total of 27 hours of ship time. The continuous use of an Ultra Short Base Line (USBL) system from the mother ship is also in general ruled out, as it commits the ship to continuously tracking the AUV, restricting the ships ability to carry out other operations.

Figure 3. The Navigation System for Autosub6000.

Instead we are planning to use range-only acoustic transponder fixes from the ship to the AUV, combined with the AUVs own dead reckoned navigation and the ships navigation, to initially position the vehicle after its descent. This approach avoids the main problem with USBL based systems – their need for extremely high pointing and attitude reference accuracy, necessitating a costly and very precisely calibrated system [11]. Using the range-only approach, we hope to be able to demonstrate (with the AUV at depths of up to 6000m) positioning accuracies as good as standard GPS.

There remains the challenge of controlling the drift of the AUV positioning system during the mission. For straight line missions, there is little option other than to hope for affordable improvements in the accuracy of the INS and ADCP systems, plus more sophisticated sensor integration and error modelling. However, for missions where an area is to be surveyed by the AUV, using optical or sonar imagery or bathymetry, and fixed natural features on the seabed can be detected and used as reference points, then there is much interest, and potential benefits in approaches such as Simultaneous Localization and Mapping (SLAM) [12] for controlling drift in the AUV positioning.

We are planning to use a similar approach with Autosub6000. Autosub6000 is fitted with a Kongsberg Simrad EM2000 multibeam bathymetric mapping system. We are developing, and in the near future plan to test, algorithms based on correlation, or Terrain Contour Mapping (TERCOM) approaches, using the data recorded from the multibeam sonar from an early part of the mission (where navigation accuracy is good) to act as a reference for later isonification of the same area, to substantially eliminate the uncontrolled navigation error growth during area survey type missions.

A combined USBL and bi-directional acoustic messaging system, the Linkquest 10000, is used for real time tracking of the AUV from the mother ship, for health monitoring, navigation, control, and to provide the ranging input to the range-only position algorithm.

Buoyancy Change

The density of sea water varies typically increases by 2.8% over a 6000 m depth range. If the materials used in the construction of the AUV do not compress at a similar rate, the buoyancy of the vehicle will change substantially as it descends.

The largest single solid item on the vehicle is the syntactic foam used for buoyancy. Prior to the trials, from manufacturers data, and through laboratory tests, we were able to get an approximate estimate of the bulk compressive and thermal moduli of this material, and also account for the other materials used in the construction of the vehicle (which generally have a very high compressive modulus, hence compress little). However, the uncertainties implicit in being able to test only relatively small samples of materials meant that we could not be certain that the buoyancy levels on the vehicle would stay within safe (always positive) limits, or alternately become so high that the vehicle would not be able to control its depth. Prior to the first ever deep water trials, then, we needed to progress with caution.

The primary issue was vehicle safety: We needed to be sure that the vehicle would maintain positive buoyancy at any depth, and hence could surface, even if all systems failed (the vehicle has two independent ARGOS satellite transmitters and flashing lights for relocation on the surface). Hence we ballasted the vehicle with a conservative surface buoyancy of 20 kg (rather than the typically used 10 kg for Autosub - a larger vehicle), and also installed two independent emergency weight drop systems, each able to increase the vehicle buoyancy by 10 kg, under automatic or acoustic communications control.

This extra surface buoyancy contingency, plus the anticipated increase in buoyancy with depth created a problem. The vehicle might have difficulty maintaining depth control or run with significantly increased effective drag due to the need to produce large down forces by hydrodynamic lift off the vehicle body.

The mitigation was to install small wings on the body, set slightly pitch down. These help in producing hydrodynamic down force with much greater efficiency (hence less induced drag) than can be produced by the vehicle body alone.

Results - Autosub6000 sea trials

Autosub6000's first test cruise, and first time in water (apart from a brief dip in its fresh water test tank to measure the initial buoyancy), was in September 2007, onboard the *RRS Discovery*. Following a short test mission in Falmouth Bay, England, to test the basic vehicle control and navigation systems, we headed for a conveniently flat part of the deep abyssal Atlantic near 47^{0} N, 11^{0} W, 250 miles way, with a water depth of 4680m.

Safely testing an AUV for the first time

Despite the design safety features already described, we still needed to proceed with great caution as we sent the vehicle down to the test depth of 4556 m. It was important to monitor the vehicle buoyancy as it descended, and abort the mission if the buoyancy started to reduce to dangerously low levels. Our approach was to make use of the acoustic telemetry and command system to monitor and control the vehicle as it descended. But how could we do this safely when the acoustic command and telemetry system had never been tested (beyond 2 m range in a test tank)?

At 0655 on September 22nd 2008, Autosub6000 was launched, the wind speed was 25 knots, the sea state was 3m. Following system checks via the radio Wi-Fi link, we sent the command to start the missions. The vehicle dived and spiralled down to 1000 m depth, and then begin circling beneath the ship. We interrogated the AUV via the acoustic communications system, and received engineering data which included the vehicle pitch, forward speed, and stern plane angles. These variables are a function of the vehicle buoyancy (Equation 1) and hence can be used to monitor the change of buoyancy as the vehicle descends.

$$B = \frac{1}{2}\rho U^2 (CL_{body}\emptyset + CL_{Splane}\delta) \qquad (1)$$

Where B = AUV Buoyancy, ρ=density of water, U =AUV speed through the water, CL_{body}= lift slope of AUV body, CL_{splane}=lift slope of sternplane, ϕ=pitch angle, δ=sternplane angle.

This data, collected while the AUV circled at 1000 m depth, served as a calibration for the system (to estimate CL_{body}), as we were confident that the buoyancy of the vehicle at 1000 m depth would not be significantly different from the (known) buoyancy at the surface. Having collected sufficient data, and satisfied that the vehicle was operating correctly, we sent an acoustic command for the vehicle to continue its descent to 2500 m. If the AUV had not received this "continue" command within a period of 1 hour of it starting to circle, it would have automatically aborted its mission, dropping its 20 kg ballast weights and surfaced. This mode of behaviour was necessary to ensure that the vehicle would behave in safe manner even if we had not been able to establish any acoustic communication.

Unfortunately, the data received at 2500 m depth revealed a problem. The AUV's speed through the water is measured by the ADCP, which relies on acoustic backscatter off particles (usually zooplankton) in the water, but at depths greater than about 1000m there was an insufficient population of zooplankton, and consequently the speed estimate had high variance and was biased towards zero. However, the consistency of the vehicle pitch angle while circling at depth convinced us that the buoyancy was not decreasing significantly as the vehicle descended, and hence we proceeded with the descent, with further circling and data telemetry stops, at 4000 m, and finally 4500m.

We still needed to find a method of accurately monitoring the buoyancy variation of the vehicle with depth, over time, and over a number of pressure cycles (it is well known that syntactic foam has a tendency to lose buoyancy over time and pressure cycles, due to collapse of a portion of its microspheres). The method we chose for subsequent missions was based on a steep angle, continuous free ascent from depth with alternately medium and very low propulsion power.

Figure 4 is a simplified force diagram which illustrates the principle.

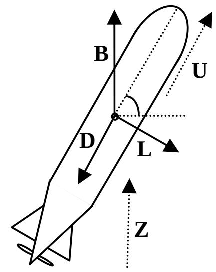

Figure 4. A force diagram for the AUV in free ascent.

There are two main benefits of this method:

- It gives a near continuous measure of how the buoyancy varies with depth as the vehicle ascends.
- The vertical speed of the AUV can be measured accurately by differentiating the output of the Digiquartz depth sensor (which itself has an inherent accuracy of 0.01%).

By resolving forces along and across the AUV axis, and assuming that the induced drag increment due to Lift is $L\gamma$, we can find an expression for the buoyancy (Equation 2).

$$B = \frac{\frac{1}{2}\rho C_d V^{\frac{2}{3}} (\dot{z}\sin(\emptyset))^2}{(\sin(\emptyset) - \gamma\cos(\emptyset))} \qquad (2)$$

where C_d = vehicle drag coefficient, $\dot{z}$ = the vertical measured speed, V = AUV volume. As γ, the drag due to lift coefficient, is known only approximately, it is desirable to ascend at as steep an angle as possible (we ran these ascents at 60 degree pitch up angles). Any steeper then there would be possibility of losing control over the vehicle roll.

Figure 5 shows the ascent velocity of the AUV as a function of time for mission #3. The propulsive power of the AUV was alternately set at 10 W (just enough to keep the propeller turning, and hence not increase the vehicle drag) and 300 W (from the powered flight data, we could also estimate the coefficient of drag).

From the variation in ascent rate we were able to estimate that the AUV buoyancy increased from 20 kg to 26 kg, from the surface to 4500m depth. The AUV was able to correctly control its depth with this level of buoyancy, even at lowest tested speeds of 1.3 ms^{-1}.

During the 5 dives during the cruise, with over 36 hours and 210 km at depths beyond 4000 m, there was no evidence of loss of buoyancy.

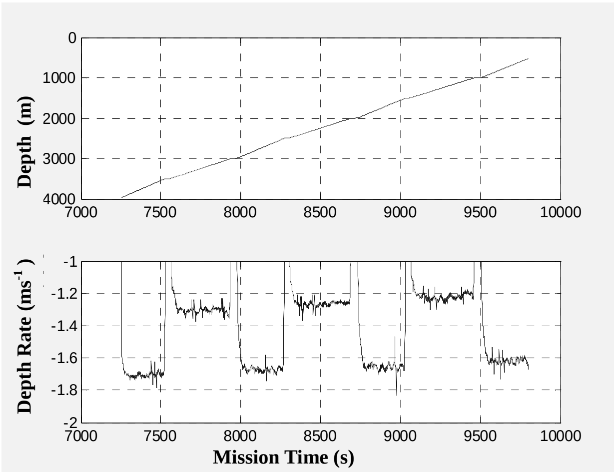

Figure 5 - The depth and ascent rate for mission #3, run alternately at 300 W and 10 W propulsion power.

Communications and Navigation

One of the objectives of the trials was to test the performance of the Tracklink 10000 combined telemetry and USBL system, and our procedures for navigating the AUV using range-only measurements. Figure 6 is a plot of the AUV navigation (uncorrected) for the first deep mission.

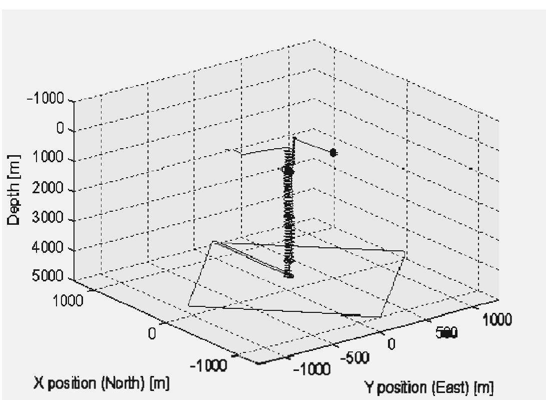

Figure 6 - 3D Navigation plot for the first deep Autosub6000 mission. The AUV spiralled to depth then executed a 1km side box at 4556 m depth.

By combining the AUV's own self navigation (as it executed the 1 km side, square course around the ship, at 4556 m depth and an altitude of 120 m above the seafloor), with the ships navigation, and the ranges from the ship to transponder on the AUV, we were able to calculate the amount by which the AUV navigation had drifted during its descent to the seabed. The solution in this case was, East: -368m, North: 848m. One approach to estimating the robustness and accuracy of this approach is to evaluate the solver residuals (calculated for the horizontal radial error), for every one of the 130 range measurements (Figure 7). The low scatter and maximum values of these residuals is a strong indicator of the robustness of this method. The solver uses all of these data to produce a single position estimate. Good results could be obtained by using only 10 ranges.

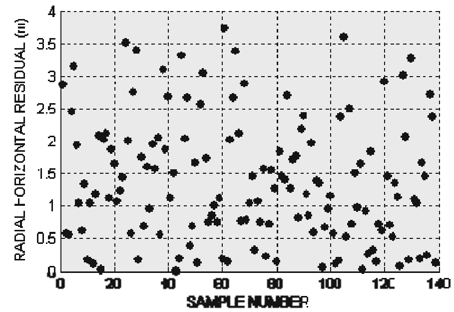

Figure 7 - The absolute values of horizontal range residuals for all of the ranges measured between the ship and the AUV as the AUV executed a 1 km side box around the ship at 4556 m depth.

After its seven hour first dive the vehicle surfaced, and was recovered onto the launch and recovery system (Figure 8).

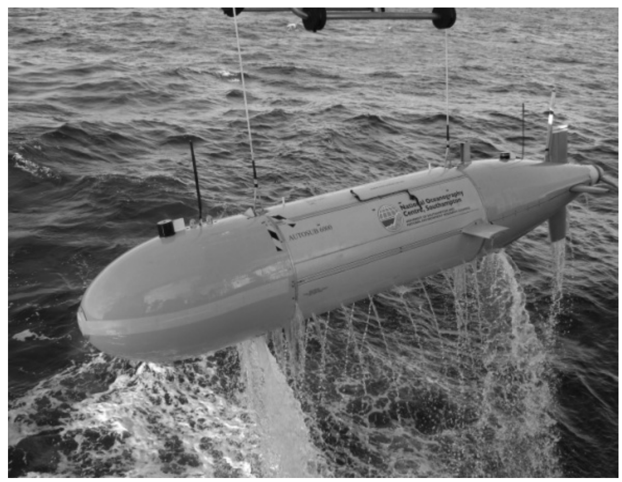

Figure 8 - Autosub6000 lifted into its recovery cradle following its first deep mission to 4556 m. The small wings, used to more effectively generate down force, can be seen near the aft end of the cylindrical centre section.

On subsequent dives we programmed the AUV to head south for 5 km and back, while the ship remained more of less stationary. The USBL and telemetry system tracked, and continued to reliably send and receive telemetry messages up to a horizontal range of 7000 m, confirming the suitability of the system for AUV operations to its depth limit of 6000 m.

Conclusions and Future Work

The trials in September 2007 were a success. The AUV controlled, navigated and communicated as designed, and the batteries worked without any problems. The range-only navigation algorithms were tried and tested in post processing mode, and the results looked very promising as a solution to the initial positioning problem.

The next deployments for Autosub6000, in August 2008, will from the *RRS James Cook*, as part of a geology and geophysics cruise to investigate potential geo-hazards (such as Tsunami generating landslides) on the European margin. In the spirit of true AUV autonomy, while the AUV is deployed, we plan to use the ship for seabed coring operations.

For this cruise, the range only navigation will be implemented in “near real time”. The navigation data needed from the AUV to process the position fix will be telemetered via the acoustic telemetry link, and once sufficient data has been received to calculate the navigation correction (this is expected to take between 30 minutes and 1 hour), the navigation offset will be sent by the acoustic link to the AUV. This will give us the ability to position the AUV at precisely the right starting point, so that the interesting geological features (such as scars in the sediment due to past sea bed slippage) can be surveyed efficiently with the EM2000 multibeam system.

As well as providing bathymetric data for the science missions, we are planning to apply algorithms to the EM2000 multibeam data to aid in the AUV navigation post processing. The area survey missions will be planned with sufficient area overlap to allow TERCOM type techniques to be applied to the bathymetry data, hence helping to constrain the navigation drift.

Autosub6000 has also recently been fitted with a Seabird SBE 52MP CTD. The CTD data will be available for general oceanographic purposes, but also will provide engineering data, improving the quality of the navigation data and bathymetry data, particularly through measurements of the depth averaged density profile (for more accurate pressure to depth conversion), and measurement of the depth averaged sound velocity (providing more accurate multibeam bathymetry, and sound velocity range correction for the range-only navigation algorithm).

These developments are the near term. For our longer term goals, as part of the NERC funded Oceans 2025 programme, we are planning to develop further the capabilities of the AUV, improving the collision avoidance and manoeuvrability (including hover mode), the autonomous navigation, and the onboard intelligence, giving it the capability of carrying out missions more effectively in complex environments.

Acknowledgments

Autosub6000 is being developed at the National Oceanography Centre, Southampton, with funding from the UK Natural Environment Research Council. I would to thank all my colleagues involved in the Autosub project, and the Master and crew of *RRS Discovery* cruise 323.

References

[1] German C. R., Connelly D. P., Prien R. D., Yoerger D. R, Jakuba M., Bradley A., Shank T., Nakamura K.-I., Langmuir C., and Parsons L. M. 2005. New techniques for hydrothermal plume investigation by AUV. Geophysical Research Abstracts, (7). European Geosciences Union.

[2]Henthorn, R., Caress D., Thomas H., McEwen R., Kirkwood W., Paull C.K., and Keaten R. 2006. High-resolution multibeam and subbottom surveys of submarine canyons and gas seeps using the MBARI mapping AUV. In Proceedings of the Marine Technology Society / Institute of Electrical and Electronics Engineers Oceans Conference, Boston, Massachusetts.

[3]Opderbecke, J., Laframboise, J. M. 2007. AUVs for oceanographic science at IFREMER, project progress and operational feedback, In Proceedings of Oceans 2007 :1-5.

[4] Wadhams, P., Wilkinson J. P., and McPhail S. D. 2006. A new view of the underside of Arctic sea ice. Geophys. Res. Lett. 33 L04501.

[5] Nicholls, K. W., Abrahamsen, E. P., Buck, J. J. H., Dodd, P. A., Goldblatt, C., Griffiths, G., Heywood, K. J., Hughes, N. E., Kaletzky, A., Lane-Serff, G. F., McPhail, S. D., Millard, N. W., Oliver, K. I. C., Perrett, J., Price, M. R., Pudsey, C. J., Saw, K., Stansfield, K., Stott, M. J., Wadhams, P., Webb, A. T., Wilkinson, J. P. 2006. Measurements beneath an Antarctic ice shelf using an autonomous underwater vehicle. Geophys. Res. Lett. 33(8) L08612.

[6]Pebody, M. 2008. Autonomous underwater vehicle collision avoidance for under-ice exploration. In Proceedings. IMechE, Part M: J. Engineering for the Maritime Environment 222:53-66.

[7] Stevenson P., Millard N. W., McPhail S. D., Riggs J., White D., Pebody M., Perrett J. R.,. Webb A. T, 2003. Engineering an Autonomous Underwater Vehicle for under ice operations, In Proceedings OMAE 2003.

[8]Wilson, R.A.; Bales, J.W. 2006. Development and Experience of a Practical, Pressure-Tolerant, Lithium Battery for Underwater Use. OCEANS 2006 :1-5.

[9]Bjerrum A., Griffiths G. eds. 2002. Technology and Applications of AUVs. Overseas Publishing Associates OPA (UK) Ltd: 213-215.

[10]Griffiths G. 2007. RRS James Cook Cruise JC009T. Trials of the Isis Remotely Operated Vehicle. Technical Report, National Oceanography Centre Southampton Cruise Report, No. 18. National Oceanography Centre Southampton.

[11]Jalving B., Griffiths G. eds. 2002. Technology and Applications of AUVs. Overseas Publishing Associates OPA (UK) Ltd: 179-201.

[12]Kinsey J. C., Eustice M. R., and Whitcomb L. L. 2006. A Survey of Underwater Vehicle Navigation: Recent Advances and New Challenges. In Proceedings of the 7th Conference on Maneuvering and Control of Marine Craft (MCMC’2006). IFAC, Lisbon, 2006.