DELPHIN2: AN OVER ACTUATED AUTONOMOUS UNDERWATER VEHICLE FOR MANOEUVRING RESEARCH

A. B. Phillips, L. Steenson, E. Rogers and **S. R. Turnock,** University of Southampton, UK, **C. Harris,** University of Birmingham, UK and **M. Furlong,** National Oceanography Centre, UK

SUMMARY

Delphin2 is a hover capable torpedo style Autonomous Underwater Vehicle (AUV), developed at the University of Southampton to provide a test bed for research in marine robotics, primarily to enhance the manoeuvring capability of AUVs. This paper describes the mechanical design of the vehicle and its software architecture. The performance of the vehicle is presented as well as preliminary findings from the vehicle's first fully autonomous video survey missions in Lough Erne, Northern Ireland. It is interesting to note that the low-cost of the vehicle and its development using a succession of MEng and PhD students has provided an excellent training environment for specialists in the growing area of marine autonomous vehicles.

1. INTRODUCTION

This paper describes the Delphin2 Autonomous Underwater Vehicle (AUV) which has been developed by staff and students to complement on-going doctoral level research at the University of Southampton (UoS) into manoeuvring and control of AUVs. Previous work has included studies into: guidance and control of autonomous vehicles [1], non-linear performance of tunnel thrusters [2] and their use on hover capable AUVs [3], the use of computational fluid dynamics to aid in the hydrodynamic design of AUVs [4-7], AUV battery technologies for deep diving vehicles [8] and bio-inspired vehicle design [9-11].

The primary aim of the vehicle is to provide a reliable platform for undergraduate and postgraduate research at UoS capable of meeting the following specifications:

- Have the capability to operate in flight-style and low-speed hover modes, with full six degrees-of- freedom (DOF) controllability whilst operating with forward speed.
- Length and dry weight below 2 metres and 60 kg respectively, and a depth rating of 50 metres.
- Design focused on ergonomics and reliability, and the use of open-source software.
- Modular design to reduce costs of future modifications and ease transportation of the AUV.
- The use of components that do not require special treatment during transportation or shipping (e.g. avoiding use of lithium batteries).
- Operational duration on one battery charge of at least 8hrs.

Like its predecessor, Delphin, the hull shape of Delphin2 is based on a scaled version of the NOCs Autosub6000 vehicle [12]. Conventional survey style AUVs such as the Autosub6000 are ideally suited to performing high speed missions (>1m/s) requiring the vehicle to survey large areas of the seabed. This flight style control uses rear mounted control surfaces to manoeuvre and the vehicle become ineffective at slow speeds. Tasks requiring low speed and hover capabilities have traditionally been performed using remotely operated vehicles equipped with multiple thrusters. To investigate the feasibility of operating an AUV at both low and high speeds Delphin2 is equipped with four tunnel thrusters, two in the horizontal and two in the vertical plane to enable low speed manoeuvring, as well as four individually movable rear control surfaces, see Figure 1.

Figure 1: Delphin2 prior to trials at Eastleigh lakes.

Delphin2 and its predecessors SotonAUV [13] and Delphin [14] have competed in the Student Autonomous Underwater Challenge – Europe (SAUC-E) [15]. Held since 2006 the SAUC-E competitions challenge the next generation of AUV developers to produce vehicles capable of performing realistic missions. Previous tasks have included pipeline tracking, target identification, and wall surveys.

The aim of the work reported in this paper is to detail the mechanical and electronic design challenges associated with the development of a novel over-actuated AUV. Sections 2 and 3 detail the mechanical and electronic design based on an evolutionary process through the two prior versions of the Southampton student AUV. The development of the algorithms and process for autonomous control is given in section 4. Finally, section 5 gives an overview of the performance obtained and its use for a science mission in Lough Erne that demonstrates its potential for specific research tasks as well as for evaluating new control strategies.

2. MECHANICAL SYSTEM OVERVIEW

Delphin2 has been designed to allow post graduate researchers at the UoS and the NOC to study hydrodynamic performance and control of over actuated AUVs. This goal is reflected in the design choices made, some of which may differ from those a commercial AUV manufacturer would use to design a new vehicle.

The Delphin2 AUV is a hover-capable torpedo shaped AUV. It has a rear propeller, four independently actuated control surfaces at the rear, and two vertical and two horizontal through-body tunnel thrusters, see Figure 2. The rear propeller produces the thrust necessary for forward propulsion and the control surfaces are used to adjust the vehicle's yaw, pitch, and if desired, roll, at medium to high surge velocities. At low (and zero) surge velocities the two vertical tunnel thrusters are used to control the AUV's depth and pitch, whilst the two horizontal tunnel thrusters are used to control the AUV's yaw and sway velocity. When operating at low speeds the vehicle has the ability to control five degrees-of-freedom (DOF), but when the forward speed of the vehicle is sufficiently high the AUV has the ability to control all six DOF through selection from the possible eight actuators and is hence such operations are referred to as over-actuated.

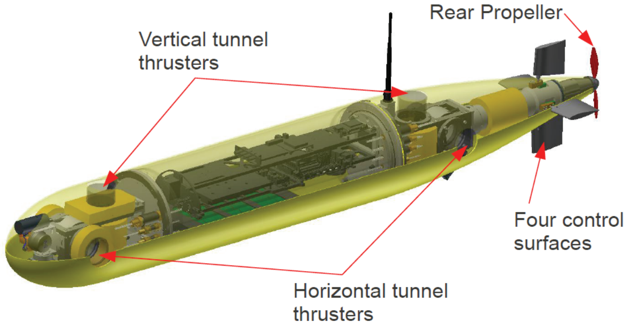

Figure 2: Delphin2 Actuators

To allow ease of transport and construction the AUV comprises of four modules; the front thruster unit, pressure vessel, rear thruster unit and the tail section. Hence, the vehicle can be quickly split into its main sections plus the fairings and then transported in a medium sized car with its support equipment. The main components will be discussed in the following sections.

2.1 PRESSURE VESSEL

The pressure vessel houses the majority of the vehicle's electronics and the battery, and has a diameter and length of 0.254 and 0.7 m respectively, Figure 3. The pressure vessel includes five main mechanical components; the outer cylinder, two end flanges and two end plates. The outer cylindrical wall is 6 mm thick and made from 6082 T6 aluminium. The end flanges are located in the cylinder at both ends using interference fits to secure their position and two O-rings ensure each joint is water-tight. Each end plate is bolted onto each end flange using four M6 bolts, and an O-ring face seal ensures the joint is watertight. To reduce corrosion of the pressure vessel the components that are in contact with water are anodized using chromic acid and two sacrificial zinc anodes are attached to the pressure vessel end plates and are electrically connected to the entire pressure vessel. Rubber moulded connectors are used to pass signals and electrical power through the pressure vessel end plates [16].

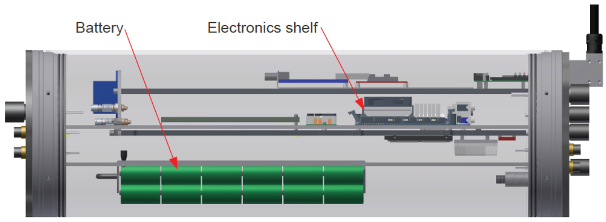

Figure 3: Pressure vessel layout.

Two pairs of rails run the length of the pressure vessel at two different levels. These rails are used to guide and support the electronics and battery shelves. The battery is located on the bottom shelf and is as low as possible within the pressure vessel so as to lower the centre of gravity of the vehicle, thus improving the static stability of the vehicle. In order to remove the battery first the front end plate is removed and the two bolts holding the battery are unscrewed. The battery is then disconnected from the electronics shelf and slides out the front of the pressure vessel. Charging of the battery can be done whilst it is *in situ* without opening the pressure vessel. The position of the battery can be adjusted fore and aft within the pressure vessel so to adjust the trim of the vehicle.

The electronics are mounted on the top shelf, which is bolted to the rear end plate. To remove the electronics shelf first the front end plate is removed and the connections with the end plate and battery disconnected. The bolts securing the rear end plate are then removed and the electronics shelf (still connected to the rear end plate) slides out. One disadvantage with this design is that the inner diameter of the end flanges restrict the dimensions of the electronics shelf and battery, therefore not making use of all the internal space of the pressure vessel. A different flange design may help reduce this problem or the empty space could be filled with stiffener rings to improve the depth rating of the pressure vessel.

2.2 THRUSTER UNITS

There are two thruster units on the Delphin2 AUV, Figure 4; one making up the front section and the other as part of the rear section. The units bolt onto the front and rear of the pressure vessel using four M8 bolts each. Each thruster unit comprises of a plastic frame, machined from sheet Acetal, onto which a vertical and horizontal thruster is bolted. Both thruster units are identical in design, therefore reducing manufacturing costs and the number of spare components. Several threaded holes are located around the unit frame which can be used to mount different sensors and devices.

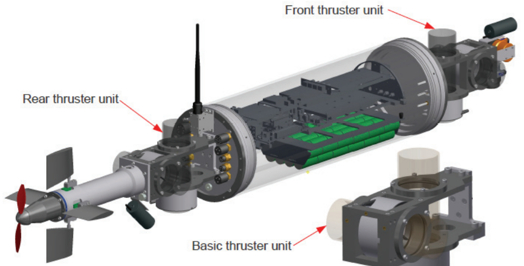

Figure 4: Thruster units.

The four thrusters used on the Delphin2 AUV are all of identical design, and are a scaled 70mm version of those presented in [17]. Each thruster has two main components; the thruster motor and the propeller, Figure 4. The motor is on the outside of the thrusters, with the motor coils potted in epoxy. The propeller is 70mm in diameter with a pitch ratio of 1.4 at 70% of the propeller radius. On the outside of the propeller are magnets that are driven by the external coils in the motor. This design provides a compact and reliable thruster that is capable of operation in depths far beyond the Delphin2 AUVs capability. The thrusters can operate at speeds of 3000 rpm, producing a bollard pull of 28 N of thrust.

2.3 TAIL UNIT

The tail unit is located at the aft of the AUV and is bolted to the rear thruster unit using six M5 bolts. It comprises of one pressure vessel, four control surfaces and the rear propeller. The pressure vessel contains four linear actuators, a brushless DC motor and gearbox, magnetic couplings, and the control electronics. The pressure vessel is made from 6082 T6 aluminium that has been hard anodized, see Figure 5, the other components are made from a mix of 316 stainless steel and Acetal plastic. A Zinc anode is fitted to the tail unit to reduce corrosion.

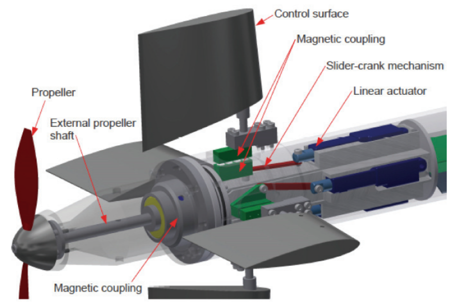

Figure 5: Tail section assembly.

Each linear actuator is mounted on separate shelves made from 6082 T6 aluminium. The linear motion of the linear actuators is converted into rotational motion using a slider-crank mechanism. The rotational torque from the slider-crank mechanism is applied, through the pressure vessel wall, to the control surface shaft using a magnetic coupling.

The brushless DC motor is coupled with a 50:1 gearbox and provides rotational torque to the rear propeller using a magnetic coupling. It is mounted in the centre of the pressure vessel between the linear actuator shelves. The use of the magnetic couplings, for both the propeller and control surfaces, improves the reliability of the tail unit substantially (compared to an oil-filled design with dynamic seals).

There are four identical control surfaces at the rear of Delphin2. These use the NACA 0014 foil profile and can be independently operated to angles of plus or minus 30 degrees relative to the vehicle. The forces generated by the control surfaces are proportional to the square of the inflow velocity of the fluid, therefore at low speeds the forces from the control surfaces are insufficient to control the vehicle.

2.4 FAIRINGS

The fairings used on Delphin2 are made up of two halves; a top and bottom half. Each half is located in position using four M5 bolts. The fairings have been manufactured using glass re-enforced plastic (GRP).

3. ELECTRONIC SYSTEM OVERVIEW

To protect the electronics from the harsh underwater environment all electronics are housed in pressure vessels. The two cameras, sonar and altimeter are housed in individual pressure vessels while the remainder of the electrical system is housed in a custom built Aluminium pressure vessel. Electrical connections between the electronics housed in the main pressure vessel and the external actuators and sensors are made with SEACON Wet-Con and Micro WET-CON wet mateable underwater connectors. Total hotel load of the Delphin2 AUV is approximately 30 W.

3.1 ENERGY SOURCE

Delphin2 has a custom built 30 Ah, 21.6 V (nominal) Nickel Metal Hydride (NiMH) battery pack. The specific energy density for NiMH material is approximately 70 W h/kg, compared to 30-40 W h/kg available in typical lead acid batteries used in the previous Delphin vehicle. The batteries are placed at the bottom of the pressure vessel to help ensure the vertical centre of gravity lies below the vertical centre of buoyancy. The longitudinal position of the batteries may be modified to adjust the trim of the vehicle.

3.2 COMPUTING POWER

The central computer is used to run the control software on the vehicle. Most of the sensors and actuator electronics are directly connected to the computer using USB or RS-232 connections. The computer has a mini-ITX form factor, a compact industry-standard design and therefore enabling the computer to be easily upgraded without substantial modifications to the electronics shelf. The computer has an Intel® Atom D525 dual-core processor 1.8 GHz, with 3 GB of RAM and a 500 GB hard drive. Peak power consumption of the computer is approximately 25 W.

3.3 MOTOR CONTROL

The thrusters utilise three phase brushless DC motors. These are controlled using a six channel motor controller (only four channels are used), designed and supplied by the same manufacturer as the thrusters. The controller uses a proprietary sensorless control method which infers the shaft position from the three power connections. This approach involves measuring the back-emf generated by the thrusters when they are spinning [18]. One disadvantage of this method is that the back-emf generated at slow speeds is too low, resulting in a minimum thruster speed of ~450 rpm.

The rear propeller is driven by a 50W Maxon motor. The motor is controlled by a motor controller that receives a pulse-width-modulation (PWM) input signal from a micro-controller. A frequency-to-voltage converter chip is used to convert the digital pulses from the motor's Hall sensors to an analogue voltage proportional to motor speed. A current sensor is used to measure the electrical current flowing through the motor controller, and outputs a voltage signal.

3.4 SENSORS

Without sensors an autonomous vehicle would be unable to navigate or collect scientific data, thus rendering the vehicle ineffective. The sensors that are permanently fitted to the AUV are used by the control systems for navigation and manoeuvring. The location of the sensors on-board Delphin2 are shown in Figure 6.

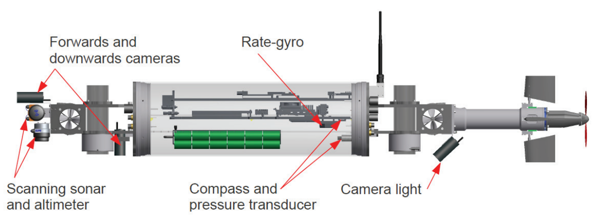

Figure 6: Sensor positions on Delphin2.

3.4 (a) Compass and Pressure Transducer

The compass on Delphin2 is a three-axis tilt-compensated digital compass with an ADC channel. It has three magnetometers and three accelerometers, that together provide vehicle bearing relative to magnetic north, and its pitch and roll angles. The ADC channel is used to measure the voltage output from the pressure transducer (rated: 0-5 bar), and in turn, this information is used to determine the vehicle's depth below the free surface.

3.4 (b) Rate-Gyro Sensor

A rate-gyro sensor is fitted horizontally within the main pressure vessel, near to the centre of gravity of the vehicle, and provides a measurement of the yaw velocity. Future development of this sensor will include combining the heading signal from the compass with the integrated output of the rate-gyro using a Kalman filter. This should reduce the magnitude of the errors between magnetic and true north caused by fluctuations in the magnetic field due to the presence of magnetic objects near to the vehicle.

3.4 (c) Scanning-Sonar and Altimeter

Both the scanning-sonar and altimeter are used to track the distance between the vehicle and sea-bed using acoustic back-scatter methods. This information can be used by the control system to maintain a defined altitude between the vehicle and seabed. The altimeter performs poorly when in close proximity to the seabed, distances less than 0.5 metres, often outputting a much larger distance. This must be taken into account when designing bottom tracking algorithms.

3.4 (d) GPS sensor

A global positional system (GPS) sensor is used to provide the location (latitude and longitude) of the AUV whilst it is on the surface. When submerged, the AUV estimates its location using a dead-reckoning approach described in section 4.

3.4 (e) Cameras

There are two analogue colour CCD (charge-coupled device) cameras on Delphin2; one pointing forwards and one downwards. These can be used, along with image processing software, to locate objects of interest near to the AUV (e.g. an underwater pipe), or collect topography data of the seabed. The analogue video signals from the cameras are digitized using a four channel frame-grabber [19] that connects to the central computer using one USB connection. The cameras are operated using the standard V4L2 application programming interface (API). The cameras can be operated with resolutions of 704x576 or 352x288, with interlaced or de-interlaced frames respectively.

A light is fitted to the rear thruster unit and is used to help illuminate the seabed and improve image quality for the downwards pointing camera. The light contains six 1 W high intensity light emitting diodes (LEDs) that can be collectively switched on and off from the central computer.

3.5 EXTERNAL COMMUNICATION

Communication to the AUV is performed using a Wi-Fi or Ethernet connection. For autonomous operation Wi-Fi is used, whilst the vehicle is on the surface, to transmit code and download data from the vehicle. A wireless access point, with an external antenna, is connected to the central computer using an Ethernet port. Wi-Fi range between the AUV and operator laptop (with a 1 W amplified antenna) is weather dependant, but on a clear day is up to 250 metres.

The Delphin2 AUV can be operated in ROV mode using an Ethernet cable to provide communications between the vehicle and operator laptop. A Short Message Service (SMS) modem is integrated into the vehicle and provides long-range low-bandwidth communication with the vehicle when it is on the surface and has Global System for Mobile Communications (GSM) network reception.

4. VEHICLE AUTONOMY AND CONTROL

The software on the Delphin2 AUV is used for the autonomous operation of the vehicle including; navigation, manoeuvring, sensor and actuator interfacing, and fault detection. Robotics Operating System (ROS), an open-source robotics platform [20], provides the underlying functionality of the software on Delphin2. The software comprises of a series of independent nodes, which are effectively standalone programs that communicate with each other and together make up, along with one central library, the Delphin2 software. Each node has a primary function, for example the compass sensor node reads data from the compass USB serial port and processes the data into usable information, this information is then published in a format that can be read by other nodes.

The ROS platform provides the communication functionality that enables the nodes to publish information to what are called topics. Nodes that require information, from another node, can then subscribe to these topics. Figure 7 provides an example of the communication method; Node A publishes information to a topic and then Node B subscribes to this topic and receives the information from Node A. Each node is able to subscribe and/or publish to multiple topics.

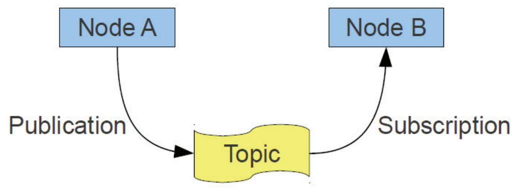

Figure 7: Communication between software nodes

The nodes can be written in either Python or C++ programming languages (other languages are currently being developed). On Delphin2, the majority of the code is written using the high-level programming language Python. The use of Python enabled rapid code development due to its relatively simple syntax, the availability of open-source libraries and that the code does not require compiling. One disadvantage of using Python over C++ is that its computational efficiency is generally lower. Therefore to achieve equivalent performance using Python compared to C++ requires a more powerful computer that will, in general, use more electrical power. As Delphin2 is designed as a research platform, electrical power consumption is not of primary concern and instead the rate of software development takes precedence.

The architecture of the software on Delphin2 can be described as hierarchical with a mission planner at the highest layer and the actuator and sensor drivers at the lowest layer, Figure 8. The main components of the software structure will be described upwards from the lowest layer.

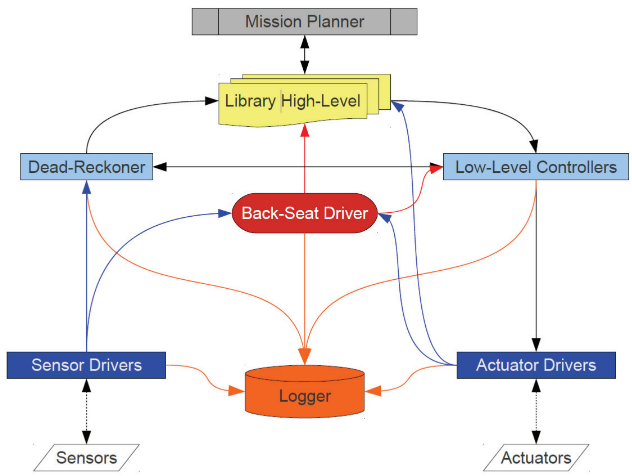

Figure 8: Software architecture.

The sensor and actuator drivers are nodes that handle the communication between the hardware and computer, sit at the lowest layer. All of the hardware (with the exception of the frame-grabber) on Delphin2 interfaces with the computer using the RS-232 serial protocol, using either a direct serial connection or a USB- serial adapter. Most of the sensor nodes only read information from the sensors and do not transmit.

The actuator nodes transmit information to hardware, such as thruster demands, and also read information returned by the hardware, such as thruster speed feedback. The processed information read by the actuator and sensor nodes are published to topics specific to each node.

The second layer includes three main components; the dead-reckoner node, the low-level controller nodes, and the back-seat driver node. The dead-reckoner node computes navigational information such as (X,Y,Z) location and surge velocity. It does this by subscribing to information from the sensors and low-level controllers and then combining this information with a five DOF non-linear hydrodynamic model of the Delphin2 AUV. The performance of the dead-reckoner is critical for navigation underwater when direct measurement of horizontal location is not typically available as the GPS signal is available only whilst the AUV is on the surface.

Also present on the second layer are typically two low-level controller nodes; a heading controller node, and a depth and speed controller node. The low-level controllers compute suitable actuator set-points so as to minimize the error between high-level demands (e.g. go to 2 metres depth) and the current vehicle states. The heading control node uses a conventional Proportional-Integral-Derivative PID type controller. Depth and speed control is more challenging control problem for a hover capable AUV as such a more advanced control strategy based on Model Predictive Control (MPC) is utilised.. The fundamental theory of MPC is to utilize a mathematical model of the system dynamics (that is to be controlled) so as to predict the future trajectory of the system for future control inputs. Using this ability, the optimal future system inputs can be found by solving a quadratic programming problem with inequality constraints. Further details of the development of the Delphin2 control algorithms can be found in [21-25].

The back-seat driver node continuously monitors sensor, actuator and mission information to ensure all the critical parameters are within predefined limits. If any of these limits are exceeded, such as maximum depth, then the back-seat driver publishes an error flag. The library high-level (described in the next paragraph) and the low-level controllers both subscribe to the back-seat driver topic. In the event of an error flag occurring, the low-level controllers immediately switch off the actuators (thrusters and rear propeller) and the library high-level informs the mission planner of the error so it can determine how to proceed.

The top high level layer will be described as two sub-layers; on the bottom sub-layer is the library high-level and on the top is the mission planner. The library high-level is a compilation of functions and system information that can be called by the mission planner. The purpose of the library high-level is to simplify and reduce the quantity of code in the mission planner, thus reducing the likelihood of a coding error.

The mission planner can then call standard pre-functions, for example ‘go to ? metres depth’, and the library high-level will publish the depth demand as well as the flags that enable the depth controller and actuator drivers. The mission planner is developed as a conventional state machine. This approach allows the rapid creation of complex missions using comparatively simple building blocks. When each task finishes it returns one of three possible outcomes; succeeded, aborted or pre-empted. Succeeded means that the task completed successfully, aborted means it did not complete successfully (often due to a predefined time-out criterion being exceeded), and pre-empted means that the task has stopped due to an error flag from the back-seat driver. The next task is defined by the outcome of the previous task. Future development of the mission planner will include more outcome options so as to enable a more reactive, and less linear, planner.

The logger node is not defined within a specific level. It subscribes to most of the available topics and writes the published information to individual files in the comma-separated values (CSV) format. These files are post-processed to analyse the vehicle performance.

5. VEHICLE PERFORMANCE

The actual performance of the vehicle has been evaluated using a mixture of laboratory and test environments, including towing tanks, wind tunnels and free running tests at Eastleigh, Testwood and Blashford lakes. These have allowed the performance to be benchmarked as well as enabling the creation of a five degree of freedom numerical model of the vehicles performance. Due to the test-bed nature of the vehicle, its performance is evolving over time, a summary of the systems current performance is provided in Table 1.

Table 1: Delphin2 system overview.

Parameter	Value
Length (m)	1.96
Max Diameter (m)	0.26
Weight in air (kg)	50
Max Speed (m/s)	1.0 (Flight style)
Min Speed (m/s)	0 (Hover mode)
Max Depth (m)	50
Dive Rate (m/s)	0.15 (Hover mode)
Turning Circle	Within own length at 0m/s 12m at 1m/s forward speed [26]
Hotel Load (W)	30W
Range (km)	20
Endurance (hrs)	8
Typical positive Buoyancy (% weight)	0.667%

The performance of the low speed control system of the Delphin2 AUV was evaluated during a number of tests conducted within the AB Wood acoustics Tank at UoS. The first test was designed to evaluate the performance of the vertical controller on Delphin2. The depth demand defined by the mission planning layer and actual depth for the mission can be seen in Figure 9. The recorded data shows the controller has a 0.2 meter overshoot when diving, and no overshoot when climbing, this was expected and was due to the Delphin2 AUV being approximately 3N positivity buoyant. The buoyancy is overcome by the through body tunnel thrusters, each of which is producing approximately 1.5N of thrust.

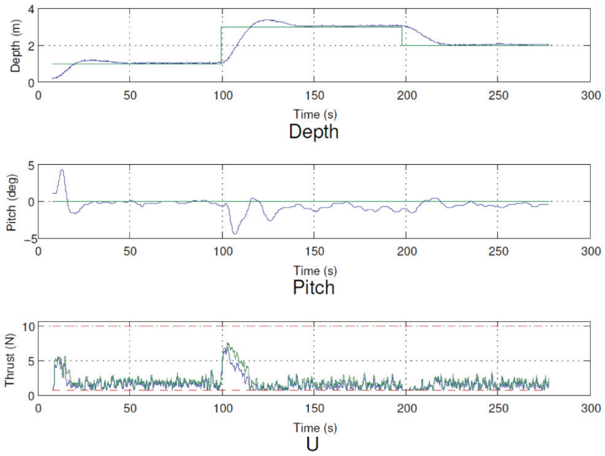

Figure 9: Experimental results of the MPC depth controller with depth set-points of 1m, 3m and 2m, at zero forward speed.

At higher speeds it is more energetically efficient to overcome the vehicle's net positive buoyancy by generating down force from the hull, rather than using the tunnel thrusters. In order, to achieve this the vehicle needs to pitch nose down using the rear control surfaces. Figure 10 illustrates the vehicle performing depth change manoeuvres at 0.75m/s forward speed. Due to the volume of water required for tests with forward speed, these tests were performed at Testwood lake near Totton, Hants.

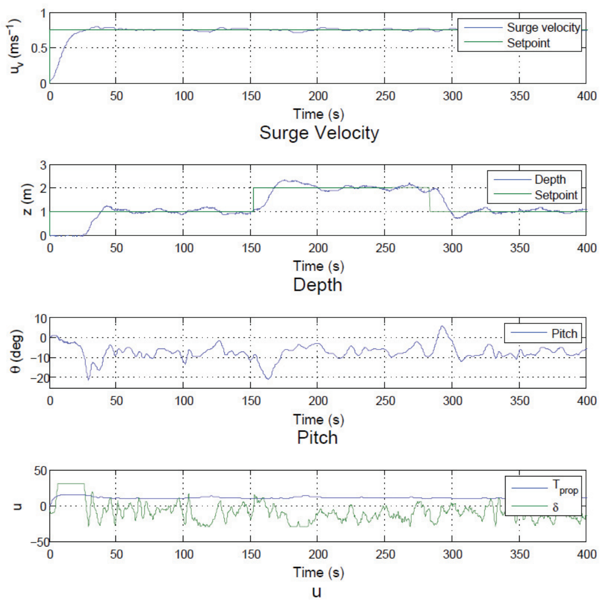

Figure 10: Experimental results of the flight style MPC depth controller with depth set-points of 1m, 2m and 2m at 0.75m/s forward speed.

5.1 LOUGH ERNE TRIALS

Development of the vehicle has progressed to a level such that its performance is both reliable and repeatable; it has therefore become a useful tool for scientific applications. Initial science trials were performed in May 2012 assessing the population of zebra mussels in Lough Erne. Lough Erne is the name of two connected lakes in Northern Ireland. These trials were based in the northern lake, Lower Lough Erne, this lake is 26 miles long has 154 islands and is the second largest lake in the United Kingdom.

Zebra mussels are small striped freshwater shellfish native to Russia and since 1996 this species has been invading Lough Erne [27], juvenile mussels (1-3mm long) attached to vessels are easily transported to new locations. This alien non-native species forms large colonies that attach to any hard surface. The presence of zebra mussels has had a significant impact on the ecology of Lough Erne, resulting in a decrease in chlorophyll and an increase in water clarity [28], yet their distribution over the lake bed has not been widely studied.

To study the distribution of the zebra mussels Delphin2 performed three transects (Figure 11) in the Carrickreagh Jetty area. Each transect mission was split into several tasks that the AUV was required to perform:

1. Navigate, on the surface, to the start location using GPS then dive to 1.5 metres depth.
2. Adjust the depth demand to achieve an altitude of 0.75 metres.
3. Proceed at 0.4 m/s on the predefined bearing whilst maintaining 0.75 metres altitude.
4. Once the transect is complete return to the surface and await a valid GPS fix.
5. Return, on the surface, to the jetty.

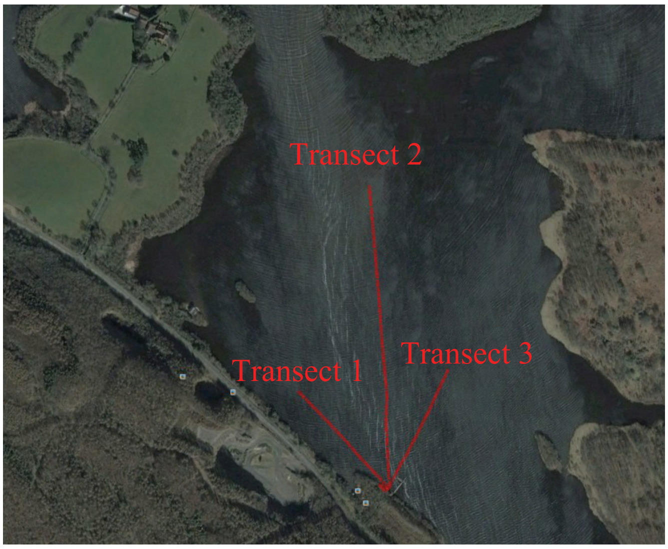

Figure 11: Transects from Carrickreagh jetty, figure generated from Google maps.

The vehicle's performance for the 2nd transect is shown in Figure 12. On the surface the position is provided via GPS, once submerged the location is dead-reckoned using a 5 DOF numerical model of the vehicle. The visibility in the lake is restricted to <2m, thus even with lights it was imperative to maintain close proximity to the lake bed in order to capture high quality images. The vehicle was able to maintain a maximum altitude of less than 1.2m, with a modal average altitude of 1m. Over these three transects the lake bed largely comprised of silt with limited isolated vegetation and small <20mm diameter freshwater sponges. An example video still is shown in Figure 13. Zebra mussels require a hard surface to colonise, thus the silty lake bed does not provide an ideal habitat however small localised colonies where observed attached to any solid detritus.

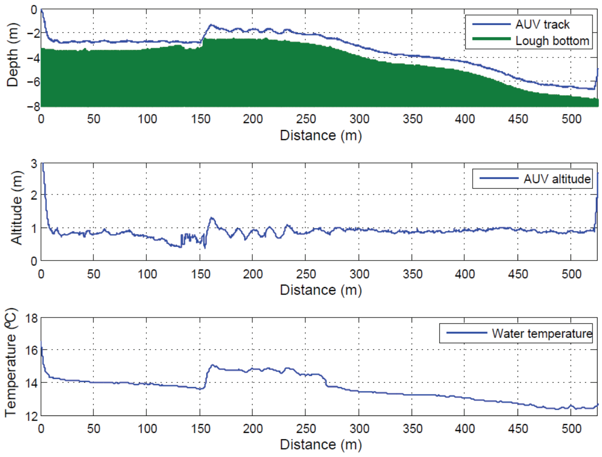

Figure 12: Depth, temperature and altitude profile for transect 2.

Figure 13: Still from video survey of transect 3.

A selection of secondary activities were also performed using the Delphin2 as an ROV for detailed inspections. The first inspection was of the underneath of the Carrickreagh jetty (Figure 14). Inspection of the jetty provided a stark contrast to that of the lake bed. Here the wooden frame of the jetty was fully colonised (below water depths of approximately 0.5m) with zebra mussels, the colony extends around the solid structure onto the silt using dead shells as a substrate.

Figure 14: Zebra mussel population on Carrickreagh Jetty

The second ROV mission was to examine the contents of a Fyke net [29] that had been laid for 24 hours aiming to capture migrating eels. The inspection of the Fyke net (Figure 15) provided what is thought to be the first underwater footage of an eel caught in this type of net.

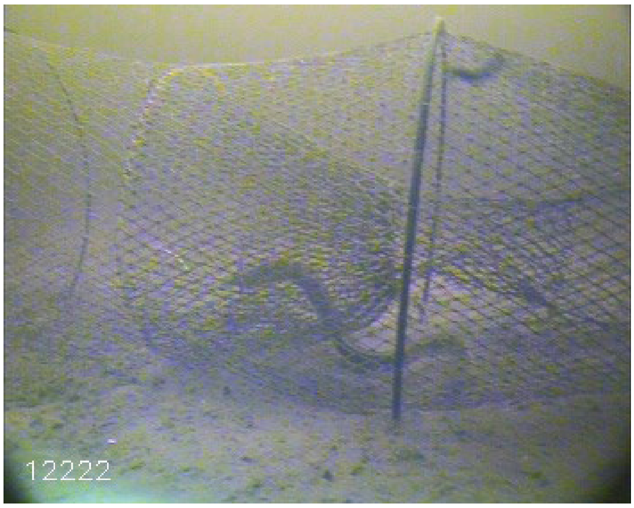

Figure 15: Eel caught in a Fyke Net, video still from ROV operations.

6. CONCLUSIONS

The principle aim of the Delphin2 program was to develop a reliable platform for undergraduate and postgraduate AUV research at the University of Southampton. To date Delphin2 and its predecessors have aided in the education of: 7 PhD students, 3 MSc students in the Fluid Structure Interactions Research group as well as: 15 fourth year group design project students and 2 individual third year project students studying on the Ship Science undergraduate course at UoS. It provides a valuable platform for hands-on research, were the modular nature of both its hardware and software make it ideal for student projects. Since, the student need only concentrate on his/her topic area, e.g. vision processing, mission planning etc.

The hybrid configuration allows the vehicle to operate at slow or hover speeds using through body tunnel thrusters, and to operate in survey mode at high speeds using the rear mounted control surfaces. Such a configuration allows the vehicle to perform missions which would be unachievable with conventional designs, providing an exciting area for research.

Development of the vehicle is on-going with a number of new students just beginning their studies. It is envisaged that in the future the vehicle will provide a platform for multidisciplinary research bringing together developers of technology with scientific end users.

7. ACKNOWLEDGEMENTS

The Delphin2 AUV team would like to thank the following companies and organisations which have provided components and expertise:

- Dan Heeks's Milling;
- TSL Technology Ltd;
- National Oceanography Centre, Southampton;
- Spinnaker Sailing Club
- AFBI - Agri-Food and Biosciences Institute

8. REFERENCES

1. JANTAPREMJIT, P. and P.A. WILSON, *Control and guidance approach using an Autonomous Underwater Vehicle.* International Journal of Maritime Engineering, 2008. 150 (A2): p.1-12.
2. PALMER, A.R., *Analysis of the propulsion and manoeuvring characteristics of survey-style AUVs and the development of a multi-purpose AUV*, in *School of Engineering SCiences*. 2009, University of Southampton.
3. PALMER, A., G.E. HEARN, and P. STEVENSON, *A theoretical approach to facilitating transition phase motion in a positively buoyant autonomous underwater vehicle.* Transactions of RINA, Part A - International Journal of Maritime Engineering, 2009. 151(A3).
4. PHILLIPS, A.B., M.E. FURLONG, and S.R. TURNOCK, *The use of computational fluid dynamics to assess the hull resistance of concept autonomous underwater vehicles* in *Oceans 2007 - Europe*. 2007, IEEE: Aberdeen. p.1-6.
5. PHILLIPS, A.B., S.R. TURNOCK, and M. FURLONG, *Comparisons of CFD simulations and in-service data for the self propelled performance of an Autonomous Underwater Vehicle*, in *27th Symposium of Naval Hydrodynamics*. 2008, Office of Naval Research: Seoul.
6. PHILLIPS, A.B., S.R. TURNOCK, and M. FURLONG, *The use of computational fluid dynamics to aid cost-effective hydrodynamic design of autonomous underwater vehicles.* Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 2010. 224(4): p.239-254.
7. PHILLIPS, A.B., S.R. TURNOCK, and M. FURLONG, *Influence of turbulence closure models on the vortical flow field around a submarine body undergoing steady drift* Journal of Marine Science and Technology, 2011. 15(3): p.201-217.
8. RUTHERFORD, K. and D. DOERFFEL. *Performance of lithium-polymer cells at high hydrostatic pressure*. in *Unmanned Untethered Submersible Technology Conference (UUST)*. 2005. Durham NH: AUSI.
9. PHILLIPS, A.B., J.I.R. BLAKE, B. SMITH, S.W. BOYD, and G. GRIFFITHS, *Nature in engineering for monitoring the oceans: towards a bio-inspired flexible autonomous underwater vehicle operating in an unsteady flow.* Journal of Engineering for the Maritime Environment, 2010. 224 (M4): p.267-278.
10. PHILLIPS, A.B., M. HAROUTUNIAN, S.K. MAN, A.J. MURPHY, S.W. BOYD, J.I.R. BLAKE, and G. GRIFFITHS, *Nature in Engineering for Monitoring the Oceans: Comparison of the energetic costs of marine animals and AUVs*, in *Further Advances in Unmanned Marine Vehicles*, G.N. Roberts and R. Sutton, Editors. 2012, IET.
11. PHILLIPS, A.B., J.I.R. BLAKE, S.W. BOYD, S. WARD, and G. GRIFFITHS, *Nature in Engineering for Monitoring the Oceans (NEMO): an isopycnal soft bodied approach for deep diving autonomous underwater vehicles*, in *Oceanic Engineering Society - IEEE AUV 2012*. 2012: Southampton.
12. MCPHAIL, S., *Autosub6000: A Deep Diving Long Range AUV.* Journal of Bionic Engineering, 2009. 6: p.55-62.
13. AKHTMAN, J., M. FURLONG, A. PALMER, A. PHILLIPS, S.M. SHARKH, and S.R. TURNOCK, *SotonAUV: the design and development of a small, manoeuvrable autonomous underwater vehicle* Underwater Technology, 2008. 28(1): p.31-34.
14. LIU, J., M.E. FURLONG, A. PALMER, A.B. PHILLIPS, S.R. TURNOCK, and S.M. SHARKH, *Design and Control of a Flight-Style AUV with Hovering Capability*, in *Proceedings of the International Symposium on Unmanned Untethered Submersible Technology (UUST 2009)*. 2009, Autonomous Undersea Systems Institute (AUSI): Durham, New Hampshire.
15. NURC. *Student Autonomous Underwater Challange Europe*. 2013 11/01/2013]; Available from: http://sauc-europe.org/.

16. Seacon. *Wet-con connectors*. July 2012; Available from: http://seaconworldwide.com/products/electrical-wet-mate/wet-con/.
17. SHARKH, S.M., S.R. TURNOCK, and A.W. HUGHES, *Design and performance of an electric tip-driven thruster.* Proceedings of the Institution of Mechanical Engineers. Part M: Journal of Engineering for the Maritime Environment, 2003. 217(3): p.133-147.
18. XI, C.-l., *Sensorless Control for BLDC Motor Drives*, in *Permanent Magnet Brushless DC Motor Drives and Controls*. 2012, John Wiley & Sons: Singapore.
19. Sensoray. *S2255 frame-grabber*. July 2012; Available from: http://www.sensoray.com/products/2255.htm.
20. QUIGLEY, M., K. CONLEY, B.P. GERKEY, J. FAUST, T. FOOTE, J. LEIBS, R. WHEELER, and A.Y. NG, *Ros: an open-source robot operating system*, in *In ICRA Workshop on Open Source Software*. 2009.
21. STEENSON, L.V., A.B. PHILLIPS, E. ROGERS, M. FURLONG, and S.R. TURNOCK. *Experimental Verification of a Depth Controller using Model Predictive Control with Constraints onboard a Thruster Actuated AUV.* in *IFAC Workshop on Navigation, Guidance and Control of Underwater Vehicles (NGCUV'2012)*. 2012. Porto, Portugal.
22. STEENSON, L.V., A.B. PHILLIPS, E. ROGERS, M.E. FURLONG, and S.R. TURNOCK, *Control of an AUV from thruster actuated hover to control surface actuated flight*, in *Specialists Meeting AVT-189/RSM-028 Assessment of Stability and Control Prediction Methods for NATO Air & Sea Vehicles*. 2011: Portsdown, United Kingdom.
23. STEENSON, L.V., A.B. PHILLIPS, S.R. TURNOCK, M. FURLONG, and E. ROGERS, *Effect of measurement noise on the performance of a depth and pitch controller using the model predictive control method*, in *IEEE/OES Autonomous Underwater Vehicles (AUV)*. 2012: Southampton.
24. STEENSON, L.V., *Experimentally Veried Model Predictive Control of a Hover-Capable AUV*, in *Faculty of Engineering and the Environment*. 2013, University of Southampton.
25. STEENSON, L.V., S.R. TURNOCK, A.B. PHILLIPS, C. HARRIS, M.E. FURLONG, E. ROGERS, and L. WANG, *Model Predictive Control of a Hybrid Autonomous Underwater Vehicle with Experimental Verification.* Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 2013. In Press.
26. STEENSON, L.V., A.B. PHILLIPS, M. FURLONG, E. ROGERS, and S.R. TURNOCK, *Maneuvering of an over-actuated autonomous underwater vehicle using both through-body tunnel thrusters and control surfaces*, in *17th International Undersea Untethered Submersible Technology Conference*. 2011, Autonomous Underwtaer Vehicles Applications Center: Portsmouth, New Hampshire.
27. ROSELL, R.S., C.M. MAGUIRE, and T.K. MCCARTHY, *First Reported Settlement of Zebra Mussels Dreissena polymorpha in the Erne System, Co. Fermanagh, Northern Ireland.* Biology and Environment: Proceedings of the Royal Irish Academy, 1998. 98B(3): p.191-193.
28. MAGUIRE, C. and C. GIBSON, *Ecological change in Lough Erne: influence of catchment changes and species invasions.* Freshwater Forum, 2005. 24(1): p.38-58.
29. THORPE, J.E., ed. *The eel*. Fifth edition ed. 2003, Blackwell Science Ltd: Oxford.

