BATHYMYSIS – THE BURST AUV

K.M. Collins[1], G. Brindlinger, A.L. Coxon, G.M. Klimaytys, C.P. Pattinson, P.R. Riggs, C.L. Wallis, G.S. Waterhouse, W.M. Megill

Abstract

A technical description of the Bathymysis is given. The Bathymysis is the AUV put forward by the Bath University Racing Submarine Team (BURST) for the 2006 SAUC-E competition. BURST is principally a student group, although postgraduates, academic staff and technicians are involved as well.

The main components of the submarine are discussed, highlighting the major design considerations and decisions that have taken place throughout the project. Also discussed are the design modifications that are considered for the future.

The submarine itself is a pressurised hull within an open frame. The propulsion system is still to be decided upon but the modular nature of the design has allowed the concurrent development of a conventional propeller drive and a biomimetic fin drive.

Hardware has been tested underwater with success. Attempts at determining the speed of the submarine have been made and a choice of fin has been made based on these underwater experiments. Numerical analysis has been useful in suggesting improvements to the design in the case of drag reduction.

The vision system has been tested on the bench and underwater and has achieved its goals with success.

Many components are still in development and the design to be used during the competition is yet to be finalised.

1 Introduction

The Student Autonomous Underwater Challenge – Europe (SAUC-E) is a competition designed to foster links within the engineering community, between industry and academia and between students and professional engineers. It aims to recreate the successful competitions that have taken place in recent years in the US. Eight teams will compete, of which the University of Bath's BURST[2] is one. What follows is a technical description of the University's entry for 2006: from internal components to overall design. The main purpose of this report is to justify the principal design decisions that have taken place and to highlight some of the background work that has gone on. The first test results are also described and future design modifications are discussed. Final design decisions have not been taken at the time of writing and, therefore, are not included. In the interest of extending knowledge in the area of small submersibles, this report is deliberately detailed where possible.

BURST is largely comprised of final year undergraduate mechanical engineers. Due to the way the engineering programmes are run at the University, these students will each have a domain of engineering they prefer and so will bring knowledge from many different areas to the team. In the spirit of interdisciplinary exchange, the team also has members from the Computer Science and Electrical Engineering departments, two postgraduates from Biomimetics are involved and the project supervisor is a physicist, turned biologist, turned engineer.

The final year students each have to write a project report/dissertation as part of their degree, from which this report is largely drawn. This has allowed the team to be aware of the underlying theories

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[1] Corresponding author: K.M.Collins@bath.ac.uk

[2] Bath University Racing Submarine Team

concerning each element of the submarine's design, so that suggested modifications can be justified with suitable evidence.

The submarine existed before the competition was entered; however, it bears little resemblance to its former self. Conceptually designed by a third year project group, the bulk of which are now in BURST, the submarine took shape over summer 2005. Unmanned submersibles can be largely divided into three main groups consisting of Towed Submersibles, tethered Remotely Operated Vehicles (ROVs) and untethered Autonomous Underwater Vehicles (AUVs). The vessel, named after a certain fish type and the obvious reference to the University, was an ROV developed for ecology research off the West coast of Canada. Its success had been limited as it was more of a concept vessel than a fully operating submarine. Since then, modifications have been undertaken or planned for nearly every part of the submarine, turning into the AUV to be used in the competition.

It is assumed that readers of this report are well versed in engineering and other aspects concerning submersible vehicles, for this reason some details may go unexplained as the reasons for them should be apparent to the audience. For more technical information on any of the components, the reader is invited to contact the authors.

2 Design of the Submarine

The design of the submarine has developed over a period of two years, starting life as a concept vehicle for a third year student design exercise. For this reason, the AUV does not have the advantage of an initially optimal design. Rather, just as with other great engineering technology, the design has evolved to continually improve when its necessary resources (people, time and money) have allowed.

The budget for the submarine had been minimal compared with the vast sums that are used in other industries for R&D work. This has kept the designs and use of materials modest. Where possible, "everyday" items have been used and often for things other than their intended purposes. This is in keeping with certain design theories that seek to "make the strange familiar and the familiar strange" through novel use of objects.

In keeping with the research direction of the laboratory to which it is associated, much effort has been made to keep the submarine "biomimetic" in design. This is most evident in the propulsion system, where flapping fins are used in favour of the "conventional" propulsion of propellers.

2.1 Frame

In the design of the frame, the initial operating environment was considered a driving factor. The submarine began life as a test remotely operated vehicle (ROV) that was to be used in searching for mysids, a food source for grey whales, off the coast of Vancouver. In this remote environment, flexibility and simplicity are key. The frame is made so that individual beam designs are repeated, allowing them to be replaced quickly and easily. The beams are made of aluminium L-section and square-section beams, easy to source in most areas of the world.

The cage-like nature of the frame protects the softer plastic hull from damage from rocks and other obstacles found near the seabed. Onto the frame can be bolted the various components needed for each mission: fins and their motor boxes; air cylinder, sensor boxes etc. Its octagonal outline (as seen from above) allows the fins to be mounted in (at least) two configurations as shown in Figure 1. The open nature of the frame, whilst causing streamlining problems, allows a stable and rigid on-land platform for the vehicle: the submarine can be inverted and sit on its back should work need to be carried out on the underside. By providing so many possible attachment points, it also permits the submarine to be easily lifted and manoeuvred out of the water.

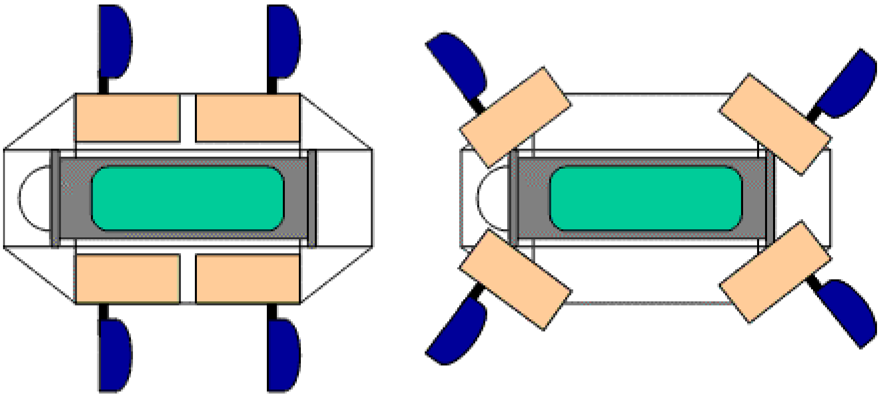

Figure 1 – Two fin configurations are possible due to the frame's octagonal shape, view from above

The frame fits around the main hull, detailed below.

2.2 Hull

Unlike manned submersible vehicles, the hulls belonging to AUVs only need protect the internal components/payload from the various hydrostatic operating pressures. The maximum depth to which the submarine was tested in the field was around 30m. To be able to withstand the pressure at this depth, approximately 3 bar, the design of the hull needed to include pressure vessel theories or another solution needed to be found.

It was highlighted in the initial design phase of the BURST 2005 AUV that one of the most significant operating costs would be that of the pressure-tight and watertight seals required to preserve structural integrity [1]. A subsequent study of available literature inspired a design improvement strategy particularly focussed upon the reduction of drag to reduce power and propulsion demands whilst not compromising structural performance. At the time of writing, no drag reduction measures have been taken and the first incarnation of the hull is still being used. Inside this hull are the workings of the submarine, the "guts", detailed further in section 2.4.

2.2.1 Main body

The original hull is a PVC-U ventilation pipe with an outside diameter of 200mm and a 3mm wall thickness. Flanges are glued onto either end of the pipe that allow the hull to be bolted onto the external frame and that allow the end caps to be fixed to the hull.

2.2.2 End caps

There are two different designs of end cap: the quasi-hemispherical dome (bow) and the flat end plate (stern), though they are both made of polycarbonate. Polycarbonate is extremely tough, and does not shatter under sudden impact, making it ideal for this use. Both ends are bolted onto the hull flanges and are kept watertight due to the o-rings that sit in recesses in the hull flange. These o-rings are compressed as the bolts are tightened.

The dome at the front of the submarine affords a good view of the submarine's surroundings to the internal camera. The dome was made by vacuum forming a flat polycarbonate sheet. This is a difficult process: polycarbonate contains trapped moisture that tends to vaporise when heated, forming tiny bubbles and causing it to turn opaque. Special care has to be taken when heating and preparing the plastic to avoid this.

At the other end is the only flat surface of the submarine hull: by designing the end plate to be flat, making the exit points for all the connectors and cables was made easier. The connectors/controls that exit the interior of the submarine include an Ethernet connection, allowing the AUV to revert to an ROV, the power switch and an air/signal cable tube, detailed in the following section. All the connectors have been chosen for their applicability to the underwater environment and are rated to IP68, the standard required for submersion of components under pressure.

2.2.3 Pressurisation and buoyancy

In order to allow the submarine to function in the field at considerable depth, the hull needs to withstand large pressures. To keep the cost (in terms of money, volume and drag) of the hull down, its design needs to be as simple as possible. This contradiction led to the development of the internally pressurised hull. This idea is not novel: submersibles have used oil-filled or flooded hulls in the past to equalise pressure, but its implementation is certainly innovative.

The system is analogous to that used by a SCUBA diver: air contained in a pressurised cylinder is released into the submarine to equalise the external pressure, which depends on the depth of the vessel. The hull, the buoyancy boxes and motor boxes are all linked to the same air supply and can be seen in Figure 2.

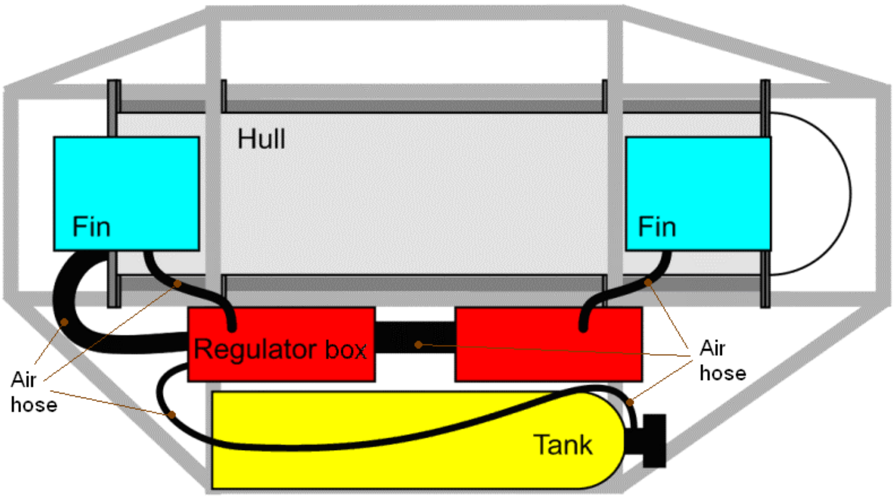

Figure 2 – Air passes around the submarine hull and the fin boxes via the air hoses

A diving regulator is mounted in the buoyancy box wall. The regulator consists of a flexible rubber diaphragm that deflects inwards when the external pressure increases, causing an air valve to open and releasing extra air into the submarine. The consequent rise in internal pressure pushes the diaphragm out again, to its normal state. As the submarine rises and the external pressure drops, the submarine releases air to reduce the internal pressure, via a dump valve. This is a spring-loaded valve designed to release air when the internal pressure reaches approximately 2 psi (0·14 bar). Further development of the pressurisation system will lead to its electronic control with the mechanical system as a back up. This will have the advantage of controlling the pressure in any orientation of the submarine, even inverted, and be able to detect pressurisation problems and then initiate corrective action.

The air is currently supplied by a 3-litre SCUBA diving reserve cylinder, capable of holding air at up to 232 bar. The air used in one mission is far less than 3 litres and a move to a smaller tank is being investigated. As the regulator is rated as 8 bar, this determines the submarine's maximum operational dive depth as 80m. After this, the integrity of the low cost sealing technology is compromised and ingress of water will occur.

The submarine is slightly positively buoyant, in keeping with the rules of the competition, so that in the event of a problem, the computer is switched off and the submarine will float to the surface. In order to complete the tasks, the submarine will need to maintain depth. This is achieved by angling the fins up or down and swimming in that direction, thus the submarine will surface or dive accordingly. A control loop is implemented within the submarine logic to maintain depth to within a tolerance. Upon leaving this tolerance, the task in progress is put on standby and a change of depth manoeuvre is effected.

2.3 Propulsion systems

The submarine has currently a number of propulsion options open to it. This flexibility is owed to the modular design of the vessel that allows changes to be made at short notice. The propulsions systems currently in the testing phase include several biomimetic devices, based on flapping foils and a more conventional propeller drive. At the time of writing a decision as to which system will be used for the competition has not yet been made.

2.3.1 Biomimetic drive

The term biomimetic refers to the application of natural technologies to engineering and science. This so-called "stealing from nature" approach gives us the benefit of hundreds of millions of years of design, testing and development upon which to draw. The advantages of this kind of methodology are evident and research groups all over the world are starting to take an interest in biomimetics.

The majority of research that has been done into single axis oscillating foils has been carried out by Nekton Research[3]. It has been found that Bollard efficiencies[4] can be as high as 75% with fins, meaning that fins are more efficient than marine thrusters [2], one of the driving factors for investigating this technology. Furthermore, a fin aspect ratio of 1 was found to produce the highest thrust to power ratio [2]. Knowing this, three types of flapping fins are currently in development for use with the submarine.

Semi rigid plastic foils

The first incarnation of fins was developed in the field in Canada. Rigid plastic food containers were sourced (salsa bottles, chunky) and the flat surfaces removed and bolted on to the motor axles. Four fins were used in total. These constituted the main propulsion system until recently when other fins were developed. The idea behind semi-rigid fins put forward by Kemp [2] is that the bending (chord-wise), due to the fluid, in the first part of the stroke allows energy to be stored in the system. This energy is then recoverable and imparted to the fluid at the end of the stroke, providing the fin relaxation frequency is the same as the oscillation frequency.

After consulting the literature, it was found that the semi-rigid "salsa" fins had a bending stiffness more or less optimised for the frequency at which they were to be used. Upon testing (for details see the section on testing), the "inline" configuration of the fins, c.f. Figure 1, was deemed to be ineffectual as the fore fins created too much turbulence for the proper functioning of the aft fins and little thrust was produced. This was remedied by extending the rear fin axles but in turn caused the overall width of the vessel to exceed the permitted dimensions.

Compliant rubber foils

It is common knowledge, especially to biologists, that the most streamlined shape is that of an aerofoil. Indeed, fish bodies are often comparable with aerofoils [3]. For this reason, aquatic robots taking their inspiration from nature often employ standard aerofoils with the exact choice depending on other constraints.

In [2] the NACA0014 aerofoil is used. In these designations (known as the "four-digit series") the first digit refers to the maximum camber as a percentage of the chord, the second refers to the location of the maximum camber in tenths of the chord length. The final two digits refer to the maximum thickness of the aerofoil, again as a percentage of the chord length [4]. Consequently, the NACA0012, the chosen aerofoil for the Bathymysis rubber fins, has zero camber (i.e. it is symmetrical about its centre line) and its maximum thickness is 12% of its chord length. Following the work done by Kemp [2], the foil has an aspect ratio of 1, meaning its span, as defined in Figure 3, is equal to its chord length. Its physical dimensions were fixed such that a useful amount of thrust could be produced without necessitating a huge test tank.

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[3] a private research company founded by Charles Pell, formerly of Duke University, MA

[4] a term that describes the ability of a propulsion device to produce thrust at zero velocity

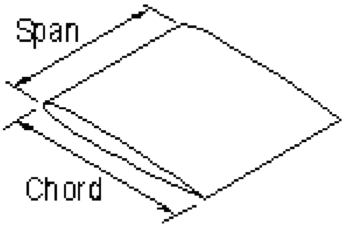

Figure 3 – Definitions relating to the compliant rubber foil, which is based on the NACA0012

The critical stiffness is to be determined experimentally (still to be completed at the time of writing) by varying the physical properties of the fin. Each fin is stiffened with a sheet of shim steel, attached to an aluminium shaft, as shown in Figure 4, and encased silicon rubber. A method was developed to quickly manufacture small quantities of the fin in the laboratory with near identical physical properties. The result of the casting process can be seen in Figure 4.

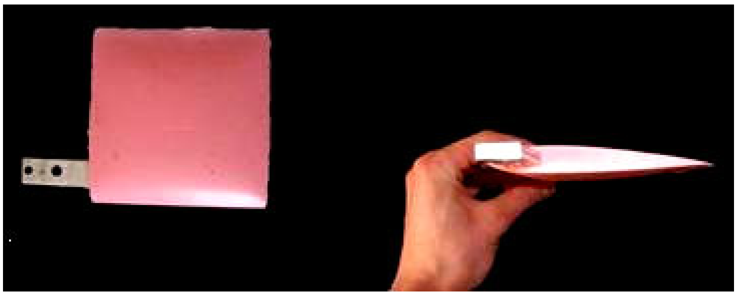

Figure 4 – Silicon rubber fin cast around the shim steel stiffener

Diver flippers

A further solution to a biomimetic propulsion system has also been proposed, the use of divers' flippers. It is thought that the larger size will produce more thrust at a given oscillation frequency/amplitude. The plastic fins have ribs running along the length that change the bending stiffness along its length, in a similar manner to the variable thickness of the rubber fins. One of the foreseen drawbacks is that these fins are designed to be used in a combined heaving (displacement along the vertical axis) and pitching (rotation about the horizontal axis that is not a conventional line of symmetry) motion (imagine the leg of a swimmer), something that the submarine motors cannot replicate. Testing will allow a quantitative measure, albeit crude, of the thrust produced.

Fin actuation/Motors/encoders

Each of the four fins is actuated by a mechanism housed in a waterproof box and connected to the hull of the submarine via a flexible tube. Each box contains a 15 W Maxon A-max 32 brushed servomotor, with a Maxon GP 32 K 35:1 ratio planetary gearbox and HEDS 5540 digital position encoder. The motors are fixed to a polycarbonate chassis, which contains a pair of gears that reduce the speed of the motor by a further 50%. The fin axle, which is linked to the gearbox, protrudes from the bottom of the chassis passing through a seal in the outer case, seen in Figure 5. Each fin is then bolted onto the fin axle.

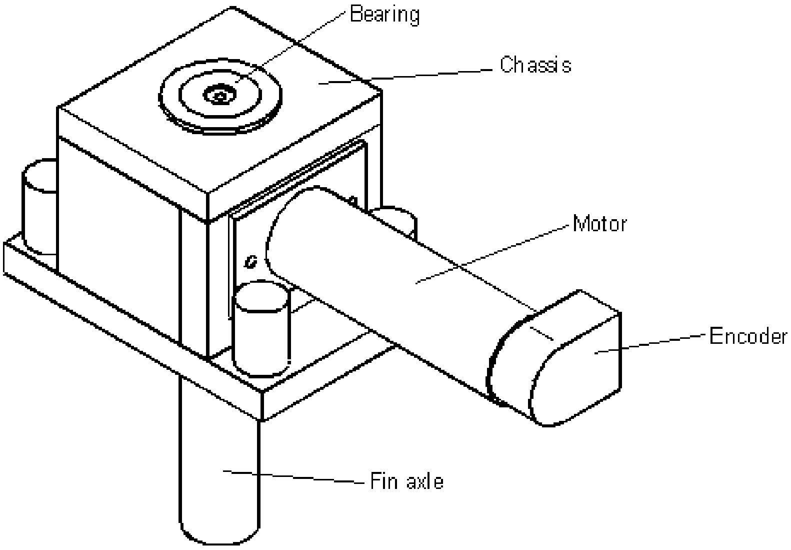

Figure 5 – The fin actuation mechanism

2.3.2 Conventional Propulsion

The use of a more conventional propulsion system is being investigated concurrently with the biomimetic options. An easy switch between the two is possible due to the modular nature of the submarine construction. A study into the use of motor driven propellers was undertaken with the aim of identifying the critical interdependent parameters that contributed most significantly to component efficiency. The approach identified the electrical, mechanical and hydrodynamic interface parameters of each of the subsystem components and related them through an analytical model.

Based on this study and on budgetary requirements, the choice of components for the conventional propulsion system was made. The recommendations of the study are given below along with the resulting component choice. Like the biomimetic propulsion system, a configuration of four modules on the oblique corners is anticipated, shown in Figure 6.

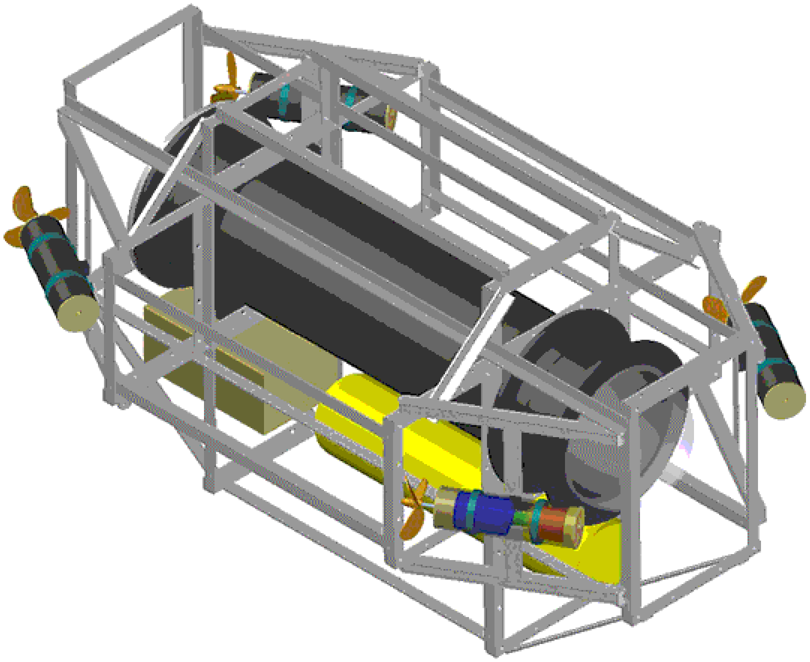

Figure 6 – Proposed four propeller configuration at the four oblique corners

The conventional propulsion modules are electrically driven by high torque, Maxon 70Watt graphite brushed motors and directly coupled to a brass 70mm diameter, three bladed propeller. The use of the brass type propellers gives improved bi-directional performance. The propeller is shrouded by a Kort nozzle assembly to give improved Bollard thrust and improved open water efficiency. The Kort nozzle also prevents damage to the propeller and the ingress of foreign objects. The propeller shaft is located in a phosphorous bronze bush and achieves approximately 1500rpm at the maximum loaded condition and generates around 15N (3.4lbf) of thrust from a 12V DC supply.

The sealing arrangement comprises of a rotary lip seal on the propeller shaft and aluminium end caps sealed with o-rings coupled with a pressured air supply to prevent the ingress of water. Each propulsion module is modular in design and comprises of two detachable aluminium end caps, a PVC casing to house the motor assembly and waterproof external electrical and air supply connectors.

2.4 Guts

All the submarines internal workings, the computer, battery, quadrature encoder module etc, are housed within the main hull. Throughout the development of the submarine, the hardware requirements have changed. The current internal unit, although crude, has been flexible enough to accommodate these changes.

2.4.1 Internal unit

It was decided that a removable multiple-shelf structure be made to fit inside the submarine hull. As the hull is a cylinder, the internal unit also takes this form. Three rods that run the length of the unit, as seen in Figure 7, provide the longitudinal structure. These are made from glass fibre reinforced nylon, which will resist any unwanted flexion/bending along the length when the unit is lifted by the rods. At each end, and in between, are acrylic plates, also shown in Figure 7.

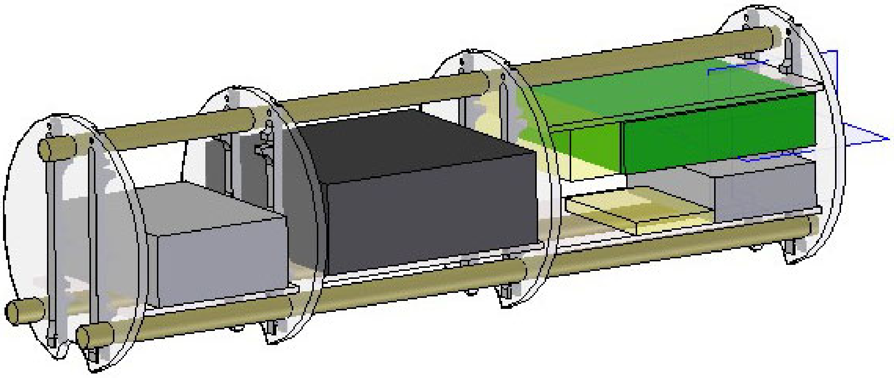

Figure 7 – Internal shelving unit making up part of the "guts", figurative representation of components

In the first incarnation of the submarine guts, the components were bolted onto individual shelves, which were attached to the acrylic plates via small angle brackets. Figure 7 shows the revised internal structure of the guts. The acrylic plate design has been revised to allow custom-made (rapid prototype) shelf runners to be included. Components are to be bolted onto their own shelf, which will then slide into its allocated section. The shelves will not move around inside the hull, as there is not much play in the radial direction but to prevent any movement whilst the guts are removed, a detachable hook and loop fastener will be employed around the rods[5].

The main advantage of this approach is that components may be changed and upgraded with minimal changes to the shelving units: the intermediate acrylic plates are free to slide along the length of the rods so shelf sizes may be changed as necessary.

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[5] This is not shown in the diagram

2.4.2 Cabling

Also apparent in Figure 7 are the curved cut-outs at the base of each acrylic plate. These serve as a channel through which the cabling is to run, allowing them to be fed to the end plate, where the cable connectors are found. The cables are restrained with a folder binding-comb that runs the length of the shelving unit. This is a cheap and novel method of restraining items, chosen for its simplicity, cost and because it is quick and easy to put the cables in and out of it.

2.4.3 Hardware

The motor controller circuit is based around an MM232R USB bridge, a dsPIC30F2010 microprocessor, and an H-bridge circuit. The USB bridge receives serial signals from the sub computer, and they are interpreted by the microprocessor. The microprocessor monitors the position of each fin by monitoring the optical encoder mounted on the back of the fin motor, and controls the motor by sending pulse width modulated (PWM) signals to the H-bridge. The sub computer uploads a waveform to the controller circuit as a series of points and then sends values for the orientation, frequency, and amplitude at which the fin is to be oscillated. The microprocessor provides closed loop PID position control, following the intended waveform regardless of external influences.

2.5 Marker Deployment

The marker is housed in an open pipe section below the main hull of the submarine. It is flooded to avoid excess volume that needs ballast. As the submarine has an excess of pneumatic power at its disposal, the sir supply will provide the force to exit the marker from its holder. At present, this system is still in development.

2.6 Power

The internal shelving unit, as previously described, can be used to house different configurations of power supply. To date, most experimentation has been performed using a single 17 Ah lead acid battery because of its simplicity and good capacity-to-cost ratio. Fowler [5] reported that lead acid cells are the most common rechargeable power source used in underwater applications because of their inexpense, ease of use, and rechargability.

The power requirements of the submarine are as follows:
- Peak demand while starting up: 48 W
- Fins flapping: 42 W
- Idle: 40 W

Therefore, with a 17 Ah battery and a reasonable safety margin, a life of around 4 hours can be expected.

To make more efficient use of space and increase operating time, other options are being investigated, notably 12 D sized battery cells and nickel-metal hydride cells.

2.7 Higher control systems – Making the sub autonomous

The goal is that the submarine should be an autonomous vehicle, which means updating the control system used when the Bathymysis was an ROV so that it can “think” for itself. Summarising the tasks, the AUV has to:

- Move from start point and submerge
- Pass through validation gate
- Identify bottom target and drop marker
- Make contact with a mid water target
- Surface within recovery zone

An overall control program logic is required to set the operations running in order. The first move must from the start point and the subsequent submerge. The validation gate must then be tackled but after that, there is a choice of which task to attempt next.

All of the tasks outlined will be modular with an overall control program running to identify completed tasks and provide the order of upcoming events. Some functionality is common to several of the modules, and where appropriate has been implemented in wholly contained external modules, which can be called upon by one of the five main elements of the high-level program, in accordance with the modularisation adopted throughout the project.

The modularity of the submarine is further evident in the software: each element, such as vision, fin controllers, and the AI, etc, knows what outputs to expect from another element of the system. This facilitates parallel development of the overall system due to the flexibility afforded to the programming elements required by each module.

The control program itself is implemented in LabVIEW, which is a graphical programming interface. Block diagrams are constructed giving a visual understanding of the flow of data and therefore it allows the user to create a program more intuitively than other programming languages

Again in the interests of flexibility, Vision and AI communicate via UDP; meaning that the two could operate on separate computers if deemed necessary, perhaps running different operating systems.

It is understood that the water in the underwater stage is treated in order to make it as clear as possible. In light of this, the vision system should be capable of perceiving targets or potential targets from any position in the pool. Therefore, an initial 360° spin (yaw) should suffice to locate the validation gate, and a spin at varying depths should locate the mid-water target and the beacon.

Should the vision system fail to pick up anything following the above strategy then the AUV will move a distance in a random direction then repeat the search algorithm from the start.

All of the subroutines explained previously will be called from within a main controller function, the AI module. The Boolean variables representing the successful completion of each of the mission subroutines can be accessed via the main function. The value of these variables allows overall mission status to be ascertained, and provides the artificial intelligence with a mission-checklist, which could be handled more intelligently if the order of tasks was not fixed.

2.8 Finding the way

For the AUV to have any chance of identifying the targets, which are both optical and acoustic in nature, then it has to be able to "see". Sight in this context does not necessarily imply using a vision system: as humans we are often biased towards this method as it is the only one we really understand[6]. For this incarnation of the Bathymysis, however, a computer vision system was required at least to identify the illuminated and flat shapes of the sunken target, which any other (such as sonar) is not able to recognise, and once implemented the vision system could easily be re-used to find the mid-water target. A system to recognise the acoustic pinger is still in development and will not be treated any further in this report.

In using computer vision systems underwater, there are some inherent difficulties. First, underwater images are widely accepted to contain more noise than images in open air or more controlled environments. Primarily though, different wavelengths of light are attenuated non-uniformly travelling through water as opposed to through air, thus, objects "change colour" depending on the distance of the perceiver. Humans are very good at ignoring the perceived colour of objects, favouring instead the "actual colour" of an object (consider that even under coloured light, the colour of an object as it would be under natural (white) light can often be guessed), whilst a computer algorithm is not as well equipped to do so. This problem was discussed at length in the dissertation of one member of the team, and two potential solutions found. An eigenmodel can be used to represent the variation of a colour over underwater distance, with which some success was obtained. Secondly, a measure of rarity

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[6] Unless, of course, one is blind.

was implemented similar to that of the University of Florida in the US competition, with which again some success was had. It is hard to find definitive solutions for such an open environment, and as such, the method of identifying the coloured targets to be used in the competition will likely be chosen after the practice runs.

2.8.1 Vision Goals

The goal of the vision system is to identify each target such that the AI, and the submarine, can respond accordingly. Below, the methods used in finding each of the targets are described in turn with occasional references to their implementation. The tasks are not described in the order in which they will be undertaken to aid the flow of the description.

As previously discussed, the goals of the vision system are focussed around the identification of coloured shapes in the scene. Again, in keeping with modularisation and flexibility, these common functions have been developed as generically as possible, and accept segmented video inputs of the target shape as training, rather than using code specific to each target (which was however necessary to find the validation gate).

Beacon recognition

The processes associated with the beacon can be split: presence of the beacon, signal detection and tracking.

Finding the location of the lit beacon is the least problematic of the tasks for the vision system. First, a rarity-based threshold is imposed on the image. Then, any blob[7] that has an average intensity greater than a high threshold and exceeds a minimum area threshold is positively identified as the beacon. Noise reduction is not used in this case, as it would smooth out the higher peaks of intensity, precisely what is being sought. The rarity-measure as it stands may be replaced by a less time consuming operation, if the algorithm is not fast enough to capture a frame under the Nyquist limit of the beacon frequency.

The flashing of the beacon, understood from the video provided by DSTL, is on for 250ms and off for 750ms. This allows the vision to examine the signal created by measurements of blob intensity in the previous 100 frames, from what it has already located as the beacon, and perform frequency analysis as a secondary check that the beacon is correctly being identified.

To track the beacon, whilst it is off or passing undetected, the Kalman filter is used. The Kalman filter is a general error tracking and linear function approximation algorithm that co-operates with the vision system. The filter can predict locations when the vision is unsure but will allow the vision to correct the filter when it is sure. Thus objects may be tracked. At each time interval: if the object position is known, the filter is told its location along with a confidence measure of the correctness of the measurement. Its state and confidence in its own correctness are thus updated. This allows the vision system to maintain continuous knowledge of the beacon's location, and hardens it to distractions by other spurious light sources such as noise or brief reflections.

Target recognition

At present, our intention is to use Fourier Descriptors to recognise both the mid-water and sunken targets. Fourier Descriptors consist of the lower order frequency components of a signal created by some measurement of the shape's border, where the signal is referred to as the shape's signature since it is unique to that shape. As mentioned previously, this allows the system to be fed a video identifying an arbitrary shape and then subsequently measure the similarity of shapes in the scene. Whilst the time available for final year projects did not allow the investigation of the effects of projection on this technique, it is hoped that our downward facing camera will not suffer from it too much.

Gate recognition

Unfortunately, due to its small surface area, and potential for its outline to be severely confused with other parts of the scene, the gate required a less generic approach. Using the Discrete Hough Transform to create a set of the lines in the image, and in conjunction with a quality measure (a mixture

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[7] Blob is a technical term for a connected component.

of expected trigonometric properties of the gate), the Random Sampling Consensus (RANSAC) method was used to identify the lines most likely to represent the gate. The quality measure operates on three randomly selected lines at a time, so that the gate may be partially obscured/off-screen and still be recognised. The distance and orientation of the gate is then ascertained by the AI from the estimated location of its four corners, with this knowledge it can attempt to navigate through the gate.

2.8.2 Vision hardware and communication

It is recognised that the vision system requires significant processing power and previous AUVs have often granted the vision system its own computer. This seems to be the most advantageous and robust solution, however limited space inside and limited power made this impractical. Still communicating over TCP/IP both Vision and AI will now reside on the same computer, running concurrently, and it is expected that the relatively slow movement of the biomimetic sub will allow enough time for both to perform adequately.

In order to allow the submarine a view of the submerged marker, it was decided that having two webcams would be advantageous as the field of view of the principal webcam will not be sufficient. A software problem between the computer vision library, OpenCV, and Windows XP meant that switching between the webcams had to be implemented with a peripheral USB switch, actuated by the AI at the desired moments.

3 Testing of the submarine

Both physical (experimental) and numerical testing of the submarine and its components has taken place and continues to take place. Indeed, as test runs are granted at the competition, testing will continue until the final competition. Detailed in this section are results from the experiments and tests done to date and their ramifications on the design on the submarine.

3.1 Numerical

It cannot be dismissed that all of the software, both mentioned and implied, has been tested for a number of cases numerically. The purpose of this section is to highlight some of the numerical analysis that has been undertaken that has directly affected, or will directly affect, the design of the submarine. It is noted, however, that due to time constraints the AI software was only tested in a virtual environment. Whilst the response of the program in this context has been validated, it is liable to change when tested with the real submarine hardware and other software modules.

3.1.1 Hull analysis

The main body was modelled and analysed with two different types of CFD software and using data from current literature, in order to investigate the drag resulting from different hull geometries. The methodology for comparing each geometry is based upon each shape being defined with the same volume and where possible the same frontal area. Volume was used as a comparison constant as the volume of water that a submersible displaces is perhaps one of the most crucial design considerations.

Performance of generic shapes was compared and rated:

Rank	Shape	Coefficient of volumetric drag
1	Dome-ended cone	0.04
2	Dome-ended cylinder	0.08
3	Sphere	0.16
4	Cylinder	0.21
5	Box	0.22

Note that the shape producing the least drag is the dome-ended cone: the shape the most like an aerofoil or a “typical” fish.

The hull of the Bathymysis was then modelled and the pressure distribution and velocity profile were calculated. This was then repeated for the hull and frame of the submarine. Further analysis of the hull as a pressure vessel, with specific material properties, yielded a limiting external pressure of 12 bar, which caused the initial failure of the flat circular end plate.

From this analysis, and experimentation in the swimming pool, the recommended optimisation strategy of the hull is to reduce its volume rather than its mass. This will allow less ballast to be used, resulting in a lower overall mass.

3.1.2 Propeller models

The creation of a model to identify the parameters that contribute most significantly to component efficiency showed that parameters exceeding the design constraints can be readily identified. The approach identified the electrical, mechanical and hydrodynamic interface parameters of each of the subsystem components and related them through an analytical model. The parametric model could be used as a predictive design tool to aid the designers' ability of making knowledgeable decisions in the selection of component hardware. Ultimately, this aids to foster greater operational efficiency and longer submerged endurance whilst still to meet the demands of high commercial off the shelf utilisation for these low cost, low power propulsion systems.

3.2 Experimental

Experiments have been conducted on various components of the submarine and of the submarine itself. The component experiments primarily took place in the context of Final Year Projects (FYPs) completed by the undergraduate members of the team. Experiments that have had a direct impact on the design, or perceived future design, of the submarine are outlined in this section.

3.2.1 Fin testing

Experimentation has shown that the optimum bending stiffness[8] of the rubber fins thus far tested is in the region of 2.2Nm^2. As expected, analysis has shown that the bending stiffness changes along the chord length (as the thickness changes). It is this change in stiffness that allows a replication of certain swimming types: either carangiform or subcarangiform. The thrust produced from the silicon rubber fins has been found to be proportional to the production of oscillation amplitude and frequency, corroborating work done by Kemp [2].

3.2.2 Motor encoder calibration

For the testing one motor was taken from the AUV and connected to the controller. The tests were not done underwater but with the fin moving through air. Underwater results may look different, however, the controller dynamics will not change. It was shown that the fin can follow any reference waveform up to frequencies of 2Hz, which is deemed adequate considering the likely operating frequency has been estimated at 1Hz.

3.2.3 Propeller tests

The delivery of power through a typical low cost, low power underwater propulsion system was assessed to identify a cost efficient method of achieving efficient propulsion for the Bathymysis AUV. This was conducted in a flow tank, based on the one built by Vogel and Labarbera [6], in which water is pushed through the 200mm square working section by a propeller and re-circulated through large diameter piping. It is though that the limited size of the working section affected the experimental performance of the propellers, introducing wall effects and "ventilation", where air is sucked into the propeller from the surface.

.The electrical, mechanical and hydrodynamic characterising performance parameters, which interface each of the component subsystems within a conventional propulsion system, were related through an analytical model. The validated model was used as a predictive design tool to make knowledge based decisions on the selection of propulsion system hardware

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[8] Bending stiffness EI, given by the equation $EI=FL^3/3d$

The study performed a series of flow tank tests with a range of motor/propeller configurations to identify the optimum performance specification for the Bathymysis AUV. The proposed conventional propulsion system configuration provides the Bathymysis with a thrust output, submerged endurance and an operational efficiency similar to a commercial AUV thruster, however at approximately 1/25th of the cost.

3.2.4 Pool tests of the submarine

The team have been fortunate to be able to test the Bathymysis in the University of Bath's 25m swimming pool. In the first instance, pool testing sought to determine the robustness of the pressure tight and watertight seals, especially around the end caps. Water ingress has not been a problem, even where the seals are not perfect. This is due to the slightly higher pressure within the hull that allows the egress of air under pressure but no the ingress of water. As a cautionary step, moisture sensors are envisaged as part of the future designs.

Ballast has also been determined from the pool tests. It is hoped with the ongoing optimisation of the submarine that the amount of ballast may be reduced, allowing the submarine to gain more points in the weight category.

Subsequent testing has focussed on the vision and the propulsion, explained in more detail below.

Vision tests in pool

A qualitative analysis of the vision system algorithms took place out of water to be used as a benchmark and was then repeated in the underwater environment during one of the numerous pool sessions. On the bench, it was found that Fourier Descriptors performed accurately and consistently. The Fourier Descriptors were noticeably affected by the transition to the underwater environment, though the majority of the classifications remained well placed. Another technique implemented at the time, whereby shapes are represented by 'Shape Descriptors', also showed significant success in identifying specific shapes, and could also be included in our final target recognition algorithms.

Testing the propulsion in the pool

Three sets of biomimetics propulsors were tested on the submarine: the semi-rigid plastic fins, the compliant rubber fins and the diver flippers. The plastic fins were only tested in the inline configuration and no test data were recorded. A qualitative observation was that minimal thrust was produced. The speed of the vessel was difficult even to guestimate, although it was in the order of cm per minute. The rubber fins and the flippers were both tested in the "oblique" configuration and data were recorded.

In a comparison of swept angle of the fins with the speed of the vessel, it is clear that at any given angle the diver flippers are the better propulsors, as shown in Figure 8. The data imply that a maximum speed can be achieved for angles around 35-40° and it would be interesting to study why this should be. However, given the errors associated with the calculation of the speed, the validity of this statement is in question. A further investigation of the effects of swept angle, for angles between zero and 180, with a more reliable way of calculating the speed is recommended. It would be of particular interest to determine the minimum swept angle that produces a high speed as Figure 8 seems to suggest a large jump between zero ms^{-1} and values above $5ms^{-1}$.

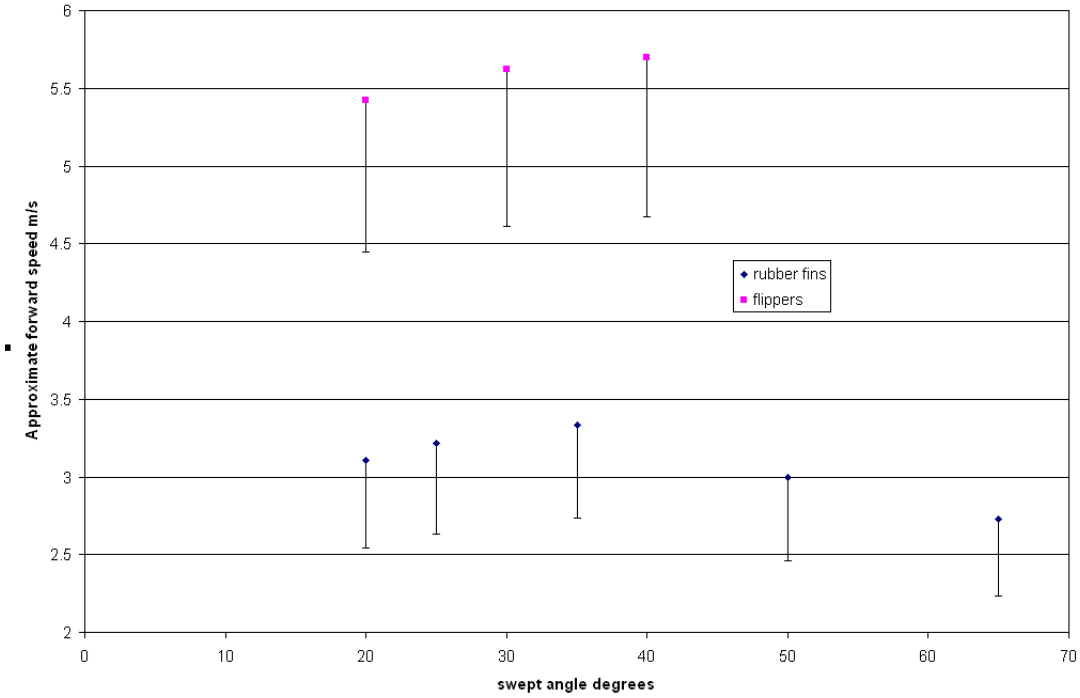

Figure 8 – By keeping the input power constant, the effect of swept angle can be compared for the two sets of propulsors, error bars represent approx 20% error

Figure 9 shows the variation of vessel speed as a function of input power for the diver fins. The different series are for the different swept angles made by the fin axle. As expected, the figure shows that for a larger input of power, a larger speed is achieved and this appears to be a linear relationship. It would be interesting to see how the rubber fins perform at lower power settings and this is recommended for further investigation.

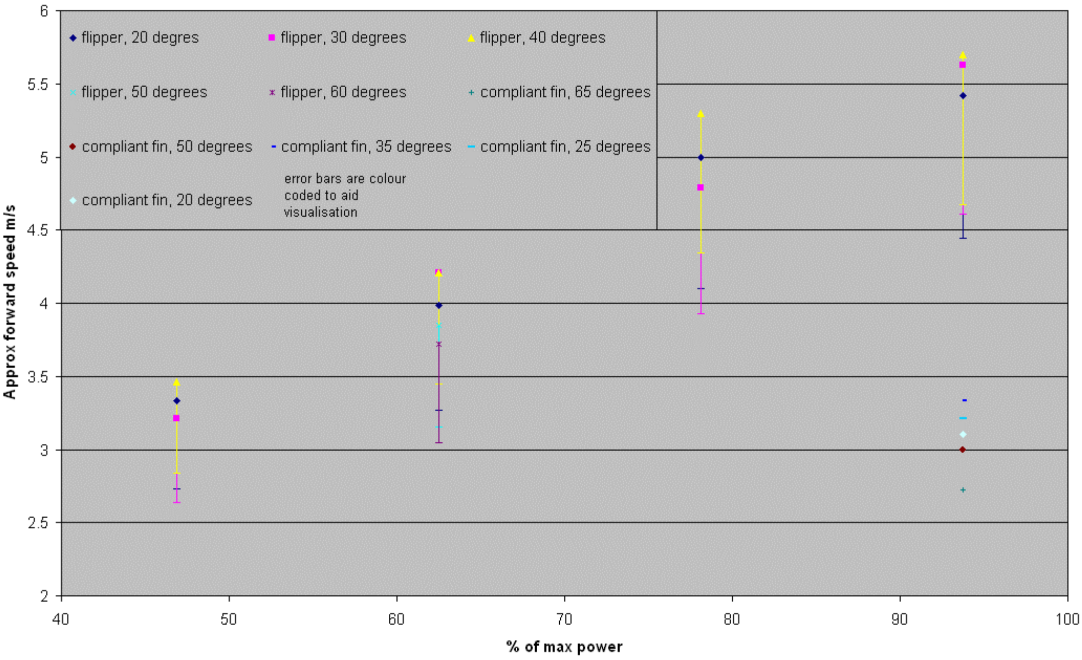

Figure 9 – Variation of swimming speed of the vessel as a function of maximum input power, different swept angle of the diver flippers is compared, error bars represent approx 20% error

Based on these findings, the diver flippers are the primary choice for the biomimetic drive system.

4 Conclusions

Following the long development of the submarine, the studies undertaken in the final year project reports and the experimentation that has been undertaken, the following conclusions are drawn:

The modular nature of submarine allows components to be improved as the necessary resources become available. This is true for the software as much as the hardware. It also has permitted two different propulsion systems to be developed concurrently, allowing a final design decision to be taken nearer the competition.

The open nature of the frame, whilst causing streamlining problems, allows a stable and rigid on-land platform for the vehicle and will protect it from obstacles on the sea bed, should the Bathymysis go into active service again. The pressurised air system of the hull ensures that there is no water ingress, although some of the seals leak air. The flat end cap allows the cable to exit the hull but the design is to be improved. In terms of the pressure vessel, this panel would be the first to fail. The hull and the frame are to be improved: drag reduction being the primary goal.

Based on pool tests of the different types of fin, the diver flippers have been chosen for the biomimetic propulsion system. The performance of the flippers was better than the compliant rubber fins for all tested values of input power. Further investigation is needed to properly determine the characteristics of the fins: however, preliminary data suggest that a swept angle of 35-40° produces the maximum vessel speed.

A conventional propulsion system, using propellers, has been found to be a viable alternative to the biomimetic propulsion system. The design was facilitated by the creation of a parametric model, which can aid the designers' ability of making knowledgeable decisions in the selection of component hardware.

The current battery choice has been deemed suitable for the submarine power requirements but it is likely to be substituted for a battery with greater power density to save on space inside the hull.

The vision system has been tested on the bench and underwater. It has performed successfully: identifying all of the necessary target mock-ups and the validation gate as constructed at the University. It is thought that a 360° yaw, or several at different depths will be sufficient for the vision system to recognise the targets.

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