Hawthorne- The Second BURST AUV

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0. Abstract

A technical description of Hawthorne 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 consists of pressurised modules within an open frame. The modular nature of the design has allowed the concurrent development of all subsystems. Hardware has been tested underwater with success. Attempts at determining the behaviour of the submarine and tuning the performance of the submarine have been successful. 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. Six teams will compete, of which the University of Bath's BURST[1] is one. What follows is a technical description of the University's entry for 2007: 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.

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

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)

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[1] Bath University Racing Submarine Team

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 the last year, using the previous BURST AUV, the *Bathymysis*, as a starting point, providing valuable lessons and reusable resources for the new craft. The move away from the previous design was chosen to establish a more reliable and robust overall design. Just as with other great engineering technology, the design has evolved to continually improve when its necessary resources (people, time and money) have allowed.

This project was initially approached as a design project aiming to optimise the mechanical design of the craft. Design analysis of the previous entry, the *Bathymysis* was performed to learn from the teams' experiences and identify the key lessons learnt to bring the team forward and develop its capabilities. Constraints on the design were applied, limiting it to a submarine that would be easy to build with a relatively low budget and limited resources while still providing a compact and reliable mechanical solution that best served its requirements.

A systems engineering approach was used in tackling the design, taking previous work done and ideas that worked well from last years entry and combining these with improved designs for the various other subsystems contained within the submarine.

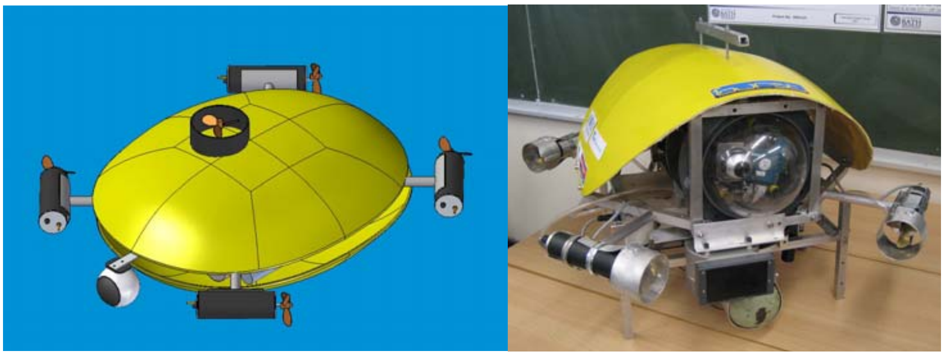


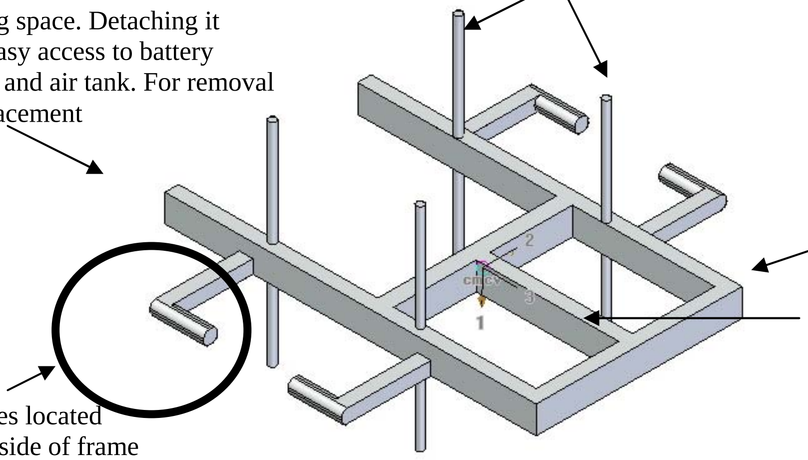
Figure 1(a) Initial design concept (b) The realised submarine with various design changes as dictated by financial, time and resource constraints

This conceptual design was realised using an iterative design approach. Most subsystems went through several prototype iterations in a move to optimise the final design and limit the risk associated with their failure. This approach ensures that any failures that occur will be limited to the subsystems tested and not affect the system as a whole. This philosophy has and will allow for the continual refinement of the design as unknown parameters affecting the performance of the vehicle can be experimented with to test and prove various design concepts resulting in a shift from original design as shown in figure 1(a) and resulting in the realised prototype, figure 1(b).

2.1 Frame

The frame is to be designed to allow for the desired modularity of the AUV itself. The frame therefore needs to be a simple platform with many suitable mounting points built in, thus allowing subsections of the AUV to be quickly and easily mounted and removed without the need to undo or remove additional sections. The frame design is also highly flexible allowing additional components to be added to the AUV without requiring a redesign of the system to incorporate them. This ensures that the frame does not limit the design of AUV or the potential for future adaptations and unforeseen use of the AUV. The frame must support the weight of the AUV and be capable of transmitting this to the ground without risk to the internal structure as well as being easily liftable by 2 people without risk.

2.1.1 Features



A detachable end beam can be used to provide additional mounting space. Detaching it allows easy access to battery modules and air tank. For removal and replacement

Locating and attachment shafts for the upper and lower shells. Shafts are threaded to allow nuts and washers to be used to adjust attachment height

6mm holes are located at 30mm intervals along all beams providing mounting points for all component mounting brackets.

Air tank attaches to the central beam

Handles located either side of frame provide easy lifting points for handling

2.1.2 Manufacturing

The frame is constructed of Aluminium extrusion welded together at all joints. All arms of the frame will have predrilled M6 holes to provide mounting points for bespoke brackets constructed for all components required by the craft. This means that components can be easily removed from the frame and attached only when needed. An important feature during the testing and building phase of the AUV. Handles are made of ¾ “ Aluminium bar, the main frame beams are made of 2” x ¾ “ aluminium extrusion.

2.1.3 Realisation

The frame design depicted above would be an ideal solution for the AUV project, however due to financial constraints as well as constraints on materials available and technical support. The frame made up for the competition has to be a compromise, taking important aspects of the design above but making a simpler easier to put together and importantly cheaper frame.

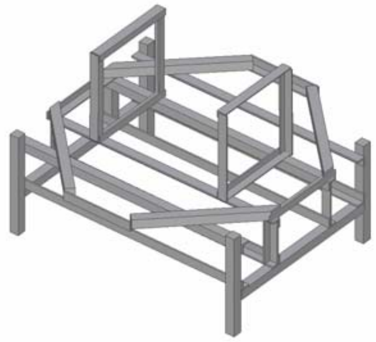


Figure 2. The modified frame allowing for manufacture without further technical support

This was achieved by re-using material from the previous year’s competition entry and creating a frame with all the desired characteristics without any additional expenditure. Due to the lack of technical support, the frame was made up using nuts and bolts as fasteners rather than the welded joints as depicted in the original design.

These measures led to the production of the frame as shown in figure 2. As can clearly be seen, this frame is much more cumbersome and larger than the ideal design, yet it retains a lot of the important design characteristics such as allowing for modularity and simple addition of new parts.

2.2 Computer Module

Submerging the electronics into water without risk of flooding is an important issue in submersible design. Not only is fail safe sealing of the critical hardware important but accessibility of the hardware is also vital to aid assembly of the hardware and make any adjustments as required.

2.2.1 Main body

The original design was a 250mm diameter PVC-U ventilation pipe with one fixed aluminium end cap and one removable polycarbonate cap. The removable end cap used an o-ring arrangement compressed by attached case clips to provide sealing and is made of clear polycarbonate to provide visual confirmation of successful sealing and allow monitoring of indicator lights. A large diameter circular pipe was chosen for improved accessibility of the internal hardware and the circular housing introduces a lesser risk of flooding compared with the square housing options explored. Being pressurised, any sealing risk is off set by air egress when in the water preventing flooding.

2.2.2 Access Mechanism

The internal housing unit is self contained and can be lifted out of the housing in one piece, fig.4(a). All connections required with the waterproof connectors in the end cap are detachable inside the housing to facilitate access. When closed, the unit fits inside the 250mm housing tightly, figure 3. The body of the housing has locating rails to prevent movement while operational.

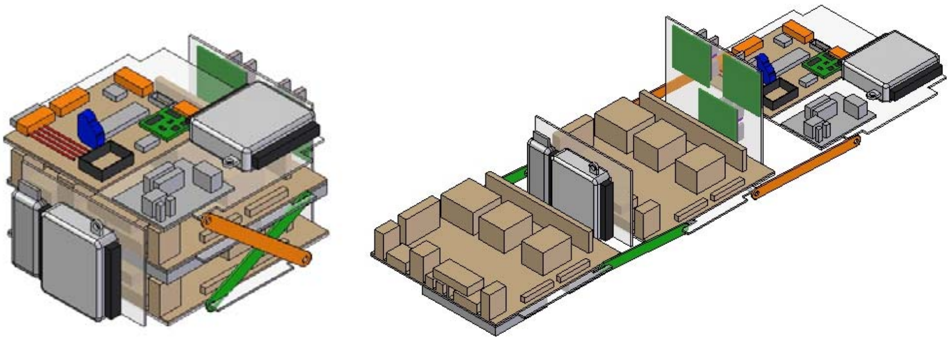


Figure 4 (a) closed internal housing unit (b) unfolded electronics unit allowing full access of all components

For access, the unit unfolds and can be laid flat, fig. 4(b). All cables between shelves run along the pivot arms or directly between shelves. These pass under or above the side walls through locating grooves to prevent tangling.

2.2.3 Realisation

However, despite the design time devoted to the computer housing, the realised solution displays a slightly modified design. Currently, this central hull comprises a PVC-U ventilation pipe with an outside diameter of 200mm and a 3mm wall thickness. A flange is glued to one end of the pipe that allows for a permanent seal with an aluminium end cap to the vessel using an o-ring compression seal. Two additional flanges are used to locate the main body without permanent attachment to prevent stresses on the body distorting and undermining seals or causing fracture to occur as was experienced by last years team.

2.3 Hardware

The central computer module consists of two PCs, one processing the visual sensors (cameras and sonar) and the other for the general running and monitoring of the submarine. The main PC is a VIA EPIA M10000G selected for its ideal layout ensuring a minimal height across the motherboard from attached memory and power supply units. The motherboard uses a 40GB Hard Disk Drive and 512MB RAM. The mini-ITX motherboard is the smallest form factor motherboard available on the market that can run on a normal Windows XP OS. This is beneficial to the development of the submarine as all future team members will be able to operate the computer having knowledge of Windows XP. This will save on debugging time especially important during time critical testing slots.

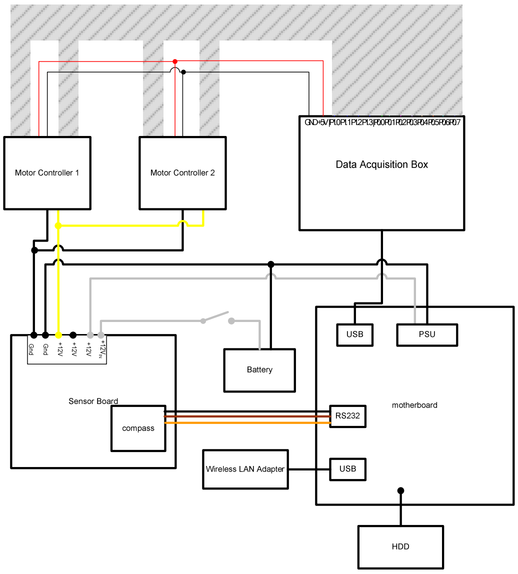


Figure 5. Computer module system as required by submarine for manual control, additional vision hardware is not depicted

Additional to the central computers, is the sensor package. This consists of an electronic compass, pressure transducer and various power and fuse connections acting as a wiring hub within the computer module.

The third section of the module houses the motor drive components. This consists of one National Instruments NI USB-6009 Multifunction Data Acquisition box to transmit the digitally generated signal to the motor controllers. The controllers used are the Pololu Dual VNH3SP30 motor controller. This being the most suitable and cost effective controller available to the team.

2.3.1 Communication

For testing, communication between the submarine and the shore is achieved using an external shore based router with a USB wireless LAN adapter providing connectivity.

2.4 Marker deployment

Markers are to be dropped upon visual identification of the underwater target, which requires the AUV to move around the pool in an initial search of the pool bottom until it can identify the target, and when correct position of the target relative to the AUV is verified a marker is released.

The marker deployment unit consists of 3 marker holders, a web cam and a servo motor and controller. Visual verification of the correct position of the target sends a signal to the servo control which in turn actuates the servo to rotate through a set angle to release the first of the markers. The servo will remain in this position, and the vision system will again work to see if the AUV is in the correct location relative to the target, if not, the AUV will again look for the target, and once correct position is verified the servo will be activated to rotate by that set angle again, releasing the second marker. This process is then repeated until the third marker has been dropped.

This system is to be tested and optimised to try to ensure that the vision system can be calibrated to ensure that the marker can be dropped straight down onto the target, this should hopefully lead to a consistent drop location. In the event of a failure to achieve this consistency, the system can easily be modified to drop the three markers at once in a cluster effect thus improving the chances of one of the markers hitting its target.

2.5 Pressurisation

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 modules. 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 sealed modules and motor housings are all linked to the same air supply.

A diving regulator is mounted in the regulator box wall. The regulator consists of a flexible rubber diaphragm that deflects inwards when the external pressure increases, causing an air valve to open releasing extra air into the submarine. The consequent rise in internal pressure pushes the diaphragm out again, to its normal state. As internal pressure rises, the submarine releases air to keep the pressures balanced, 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).

The air is currently supplied by a 3-litre SCUBA diving reserve cylinder, capable of holding air at up to 232 bar. 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 a separate depth control system

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.

2.6 Depth Control

The depth control module uses two propeller units driven by 12VDC motors applying downward thrust on the craft, pushing it to depth. Feedback and monitoring is achieved using a Honeywell pressure transducer situated inside the pressurised computer module. The computer module has an internal pressure that is slightly above the external pressure of the water and thus sensor feedback is proportional to submarine depth.

2.7 Propulsion System

Research in to various propulsive methods available informed the propulsion design for the vehicle. The first design iteration for the team was last years fin based propulsion adopted by the *Bathymysis*. The limited success and multiple limitations of this type of propulsion system, with its low speed, complexity and high power requirements led to the selection of a propeller based propulsion system for this year's design. Previous work on propeller based propulsion systems for AUVs at the University was used to aid the design of the final system

To reduce design time and make efficient use of existing resources, existing propeller motor modules were used for the design and testing of the horizontal propulsion system for the AUV. These modules had not been used by the group before and were a new addition to the team's equipment. Various tests to gauge performance were undertaken to help specify the necessary equipment required for the unit to function.

Figure 6. (a) Propulsion modules with (b) associated mechanical fastening system to submarine frame

The propulsion modules consist of a 75W Maxon Motor housed in a custom housing made in-house at the University of Bath, figure 5. The propellers used by the unit are 75mm diameter, 3 blade brass screw type propellers.

As with all attached modules, the housing unit is designed to be pressurised to overcome the risk of undermined sealing between parts and potential flooding of the motors. This is achieved by pumping air from the onboard air tank to the motors through a hose system and having an outflow of air across any undermined interfaces. A cable powering the motors passes through a M12 cable gland to the motor.

2.8 Power

The power module of the submarine is a self contained unit. To overcome the risk, batteries for AUV2007 will be housed in separate sealed modules thus eliminating the need to open the submarine and expose the internal circuitry. This removes the hazard if batteries need to be replaced while the submarine is still wet (possibly occurring if the batteries run out of charge during a testing session) as drips could hit the sensitive circuit boards and electronic parts. Being the heaviest components onboard the submarine, this unit is located centrally and low on the submarine to help lower its centre of mass relative to the crafts centre of buoyancy.

Initial design of the power module used NiMH D Cell batteries. These were chosen for their good capacity-to-volume ratio allowing for the most compact battery pack achievable with a moderate budget while being easy to charge with little risk from charging as compared to the denser capacities available from Lithium batteries which have associated risks from improper charging.

The housing is made of 75mm PVC pipe with sealed end caps. A central tube contains two rows of 7 D cells and one of 6 cells. Space is left for battery connectors inside of tube and cable attachments.

A two pin female connector lies on one end of the pack which attaches to its male counterpart with a waterproof connection. The connection is the Buccaneer PX0412 Front Panel Mounting Connector from Bulgin.

2.8.1 Realisation

The use of NiMH D Cell batteries as previously described proved a limiting factor in the realisation of the module due to the high cost associated with this type of battery pack. Financial and time constraints have lead to the comprised solution of using 2 12Ah 12V sealed lead acid batteries due to their good capacity-to-cost ratio and to provide the appropriate geometry of battery module at a budget price. The geometry of these batteries has allowed for the replacement to be made without affecting other modules and can sit in the same space reserved for the original pack. A bespoke welded aluminium sealed box has been made to protect the units in their underwater environment.

During intermediate testing, most experimentation has been performed using a single 7.2 Ah lead acid battery, being already available for this project. Fowler [1] 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.

2.9 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 *Hawthorne* 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
- Map the underwater environment
- Surface within recovery zone

An overall control program logic is required to set the operations running in order. The AUV's first task is to move from the start point and 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 writes any data to a global data file which can be called upon by any of the modules thus removing any reliance between subprograms, 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, propulsion 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 in 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 360º 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.

2.10 Finding the Way

For the AUV to have any chance of identifying the targets, 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. For this incarnation of the *Hawthorne*, 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.

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 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.

2.10.1 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).

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 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.

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.

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.

Mapping

Mapping of the obstacles in the arena will be performed by an Imagenex Technology Corp model Delta

T Sonar available to the BURST group. Processing of the signal received from the sonar will be achieved by a separate computer module as described in the electronics housing section.

The sonar has a 120 degree range in the x axis and a 3 degree rang in the y axis. To make full use of this, the unit will be mounted horizontally (as on right, fig 36) and the craft allowed to spin at various depths to map the arena.

3. Testing

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 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 meeting 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 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 Hawthorne AUV. This was conducted in a flow tank, based on the one built by Vogel and Labarbera [2], in which water is pushed through the 200mm square working section by a propeller and re-circulated through large diameter piping. It is thought 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

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

3.2.2 Pool Testing

The team have been fortunate to be able to test Hawthorne 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 not 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.

The Floating Testing Rig

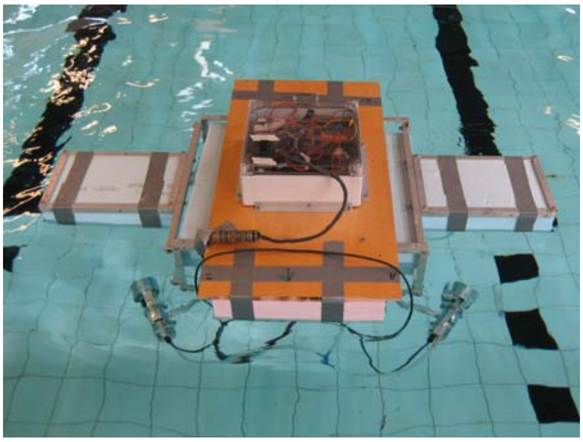


Figure 8. Floating test rig designed for initial propulsion system testing and calibration

Having a propulsion unit configuration for improved horizontal movement and basic specifications of the unit behaviour in water, a test rig was designed and built to test and characterise the propulsion system, fig.8. Concurrent to the development of the mechanical rig, the electronics required to drive it were also developed.

To overcome issues with waterproofing the valuable electronics, the rig was designed to float on the surface of the water to keep the electronics above surface level while the motors were submerged below it in the appropriate orientation.

The design was centred on reusing parts from the *Bathymysis* where possible to minimise resource use and cost before the manufacture of the optimally designed submarine. Additionally, an emphasis was placed on the modularity of the rig to ensure changes could be made quickly and easily as required. This was especially important while pool testing.

Results of testing

With all four motors at full power, the rig tended to turn in an anticlockwise arc proving the necessity of fine tuning of the craft. To compensate, the duty cycles were varied until near straight line performance was achieved. Duty cycles tended to fall within a 10% margin depending on surface disturbances. It should be noted however that the AUV will not be as sensitive as the test rig being below the surface.

To get a more reliable representation of the behaviour of the rig in the water, an electronic compass was attached to the surface rig. This recorded the bearing of the rig at 1Hz showing the general arcing trend the rig tended to have at various settings thus proving performance.

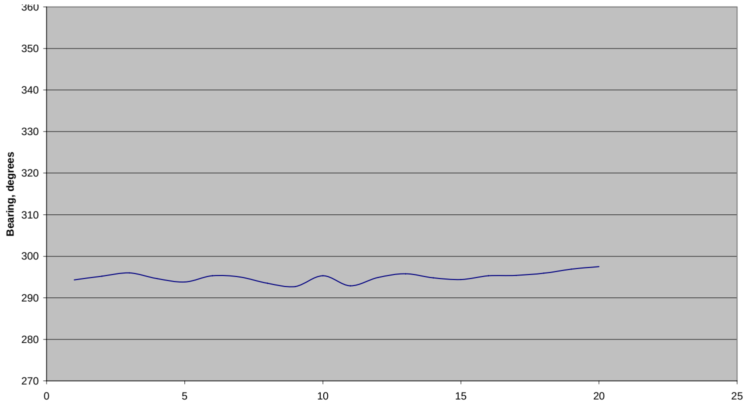


Figure 9. Reliable straight line performance within tolerance was achievable despite the effects of surface perturbations

The rig was used to optimise straight line performance with duty cycle being varied to achieve the fastest straight line speed in all directions. These tests and using the preset motor configurations resulted in optimised full speed duty cycle arrangements. Using the onboard electronic compass, the path of the craft was recorded. The peaks and troughs are indicative of the surface waves affecting craft movement. This level of accuracy of straight line performance is suitable for the AUV although smaller deviations are expected below surface.

At all duty cycle settings investigated, turning of the rig at a stationary point without translation was achieved effectively. However, the settings used were designed for straight line movement at maximum speed and proved to be too rapid for effective rotational control of the rig. This proved the need for the craft to use a slower setting for rotational movement for greater accuracy- as the rig had a tendency to continue spinning once the motors are turned off by up to 45 degrees.

From these general observations and optimisation of the rig, the behavioural characteristics of the rig directed efforts towards further control development and provided data on craft sensitivity in maintaining an orientation- an important feature for reliable control which has governed the dynamic changes to the motor settings needed to maintain accurate control.

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.

4. Innovation

Although these results cannot be directly transferred to the submarine with the same motor configuration, these results provide an indicator and show behaviour characteristics which have helped reduce calibration time for the AUV.

The large variations between propulsion thrust values and difficulty in optimisation in situ has led to the development of a look up matrix used to select the required nominal thrust required of each propulsion unit for its required directional movement. This matrix lists coefficients scaling the percentage duty cycle to the nominal thrust value produced by the unit. These results are recorded at a fixed pulse width modulation signal frequency and allow for easier tuning of the craft as the control program looks up the required duty cycle requirements for each mode of operation.

Additionally, once the whole device is submerged in the water, issues with disturbances from surface ripples will no longer factor as greatly and subtle heading changes will be more feasible. Further optimisation and testing is currently being undertaken.

5. 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 modifications to be made as and when the need has been identified and aided the realisation of the submarine.

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 Hawthorne be used as a test vehicle. 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.

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 in the future.

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 360º yaw, or several at different depths will be sufficient for the vision system to recognise the targets.

6. References

[1] Fowler, A. *Underwater Power Systems*. in *Subtech 83*. 1983. University of Newcastle upon Tyne.
[2] Vogel, S. and M. Labarbera, *Simple Flow Tanks for Research and Teaching.* Bioscience, 1978. **28**(10): p. 638-643.

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Finally, thanks go to those too numerous to mention who have had something to do with the submarine at any point.

A. Financial Summary

Many components used in the making of this craft have been sourced from existing resources available to the BURST team. Additional purchases as required for the project so far are noted below:

Component	**Specification**	**Quantity**	**Price, £**
Mechanical	Aluminium		100
	Polycarbonate		Free
	Waterproof Connectors	20	150
	Additional Connectors		Free
	Latches	4	20
	Waterproof Boxes	1	10
	Strapping	1	10
	Misc.		
Thrusters	Motors	2	16
		4	Reused from previous resources
	Propellers	3	30
Sensors	Pressure transducer	1	
	Depth Sounder	1	150
Connectivity	Wireless LAN Hub and Key	1	40
Power	SLA Batteries	2	40
	H-Bridges	5	200
	DC/DC Convertor	1	30
Electronic	Components Various		50
Imaging	Web Cam	1	30
	Sonar	10k	Free
Accommodation		8 Persons	160

B. Risk Assessment

What are the hazards	***Who might be harmed***	***What is being done to reduce risks***
Manual handling Regular movement of the AUV and constituent parts	Team members could suffer from back pain from regular heavy lifting	• Top attachment to allow AUV to be lifted in and out of water by crane • Use of trolleys to move the AUV around • Handles made on either side of the AUV to allow easy lifting for 2 people • AUV designed to keep weight to a minimum
Electrical components Batteries	Any team members handling the batteries and container, danger of electric shock	• Batteries are carefully packaged into a sealed container. • Batteries do not need to be removed from the container to be charged
AUV computer equipment	Team members working on the main internal of the AUV	• All wiring has been correctly insulated • Fuse box built into the circuitry to stop high current from running through the circuit
Fire Batteries	Team members in close proximity to the batteries or in the worst case anyone in the building with the batteries. Possibility of people suffering from smoke inhalation or burns which could potentially kill	• Batteries have been specifically selected for the duty's required in the AUV • Trickle charger has been bought to ensure that the batteries are always correctly charged
Hazardous substances Re-charging of batteries- Potential explosion by release of hydrogen, acid spills	Burns or fractures from ejected material could affect anybody nearby at the time	• Specifically chosen battery charger to match battery requirements • Batteries being trickle charged to reduce the risk of explosion • Sealed batteries chosen and stored carefully in a suitable sealed container to reduce risk of acid spills
High pressure Vessels Scuba tank	Risk to anyone in the vicinity from explosion and fracture from ejected material	• Visual and hydrostatic testing undertaken by a professional to certify the safety of the scuba tank
Pressurised componentry	Risk to anyone nearby from explosion of components and fracture from ejected material as well as causing electrical hazard if explosion occurs in the water	• Visual and hydrostatic testing undertaken by a professional to certify the safety of the scuba tank • Scuba regulator valve used to keep pressures to a suitable level • 2 dump valves in the pressure system to eject excess air to keep pressure to a suitable level
Rotating Machinery Propellers	Risk to divers or other people in the vicinity when the propellers are in motion, risk of lacerations and potential for loss of fingers etc	• Cowling built to surround the propeller blades to ensure that contact between propeller blades and human limbs cannot occur