

# HAWTHORNE 2·0 – SAME BOAT, NEW GUTS

**K.M. Collins, H.J. Brassington, M.T. Ferris, P. Glockner, J. Middleton, B.J. Williamson,  
J. Yao, S.D. Dolan, W.M. Megill**  
**Department of Mechanical Engineering, University of Bath, Bath, BA2 7AY**

## **Executive Summary**

Bath University Racing Submarine Team (BURST) presents its 2008 SAUC-E entry: the *Hawthorne 2·0*. This is an upgraded version of the original *Hawthorne*: the overall external design remains the same, but the internal components have all been upgraded, and the software completely redesigned. The AUV still has a compressed air system, which mitigates water ingress due to the slight over-pressure on the inside of the vehicle. It has also been tested at 20 m depth in the Pacific Ocean and the *Hawthorne 2·0* will return there this summer to act as an inspection class ROV. In order to be able to control the vehicle as an ROV during testing and out in the field, a GUI has been developed in LabVIEW to accommodate all the needs of the controller. When operating as an AUV, the missions are planned and executed in LabVIEW as a series of hierarchical commands. New components on the vehicle include an external pressure sensor, a re-designed marker dropper, a new battery configuration, 24V motors throughout, dual webcams, extensive machine health sensors and new motor housings. There are six motors: four in the plane, set at 45 ° to the fore-aft axis of the AUV and two positioned vertically. These allow the *Hawthorne 2·0* to move holonomically in the horizontal plane.

The vision system has been upgraded and runs on its own motherboard, while the main control software runs on another computer. This split of the tasks allows the processor intensive vision code to run as fast as possible. Images are fed to the vision system from two webcams: one forward facing and one downward facing. A map of the underwater environment will be produced by sweeping the area with a multibeam sonar, coupled with information from a compass, and superposing the images.

The current total spend on components stands at £2598, whilst revenue accounted for to date is £720. Development is still in progress, so budget totals may further change in the run-up to the competition.

## **Introduction**

The Bath University Racing Submarine Team, BURST, has taken part in the [dstl]-run SAUC-E since its inception in 2006. The first entry was a biomimetic oscillating fin propelled AUV, the *Bathymysis*. Early tests were promising but a complete flooding of the hull in the practice rounds rendered much of the important circuitry useless. In 2007, a team of reduced numbers returned with the *Hawthorne*, a more conventional propeller-driven design, but struggled to overcome software and computer hardware reliability problems, and failed to qualify. This year, the team returns with an improved, and hopefully much more reliable, *Hawthorne 2·0*.



Figure 1 – *Hawthorne 2-0*, the 2008 BURST entry to SAUC-E

## Physical and Mechanical Systems

Version 2-0 of the *Hawthorne* retains the hull, frame, pressurisation system and propulsion configuration it had in 2007, but all of its internal electronics and motor pods have been reworked or replaced. New sensors this year include a multibeam sonar, an upgraded pressure sensor, new webcams, and machine health sensors which monitor current draw, battery voltage, motor temperature, and internal pressure. The operating voltage has been increased to 24V and motor control electronics have been upgraded. 24V Maxon RE36 70W DC brushed motors have been fitted throughout, providing a greatly increased thrust and top speed. The sensors and internal architecture have been upgraded and modified to improve the *Hawthorne's* competition-readiness, while at the same time planning for its future use as an inspection-class ROV in the rugged environment of the Pacific Ocean.

### *Pressure vessel*

The hull consists of a 2' length of 8" diameter PVC pipe, which is used to house the majority of the electrical systems that form the brains of the AUV. The forward end of the pipe is sealed with a 5mm aluminium bulkhead, fixed to a circular flange glued to the outside of the pipe. An o-ring between the flange and the bulkhead ensures a water-tight seal. The aft end of the pipe is sealed with a 25mm thick transparent polycarbonate piston. Two barrel o-rings set into the radial face of the piston ensure a watertight seal with the inside of the hull. A thinner, removable polycarbonate panel is set into the piston, providing quick access to the electronics if necessary. Connectors through the access panel vary depending on the application. For both electrical and waterproof reliability, the 6 motors are connected via Lapp Kabel cable glands with electrical connections made internal to the hull using screw terminals. Bulgin IP68 (submersible to 10m) USB<sup>1</sup> (PX0843) and LAN<sup>2</sup> (PX0833) provide interconnections between the hull and various external parts of the AUV. The main power to the pressure vessel is supplied by a SEACON WET-CON connector. The power distribution is discussed in more detail in subsequent sections. Also connected to the access panel is the air hose running from the SCUBA tank situated below the hull (further details are given in the Buoyancy and Air Pressure section). This allows the hull to be kept at a slight over-pressure, reducing the reliance on seals to mitigate the ingress of water.

Inside the hull, the electronic systems are held in place on a reconfigurable shelving system, which allows all the circuits to be removed and worked on independently of the vehicle body. The circuit boards and computers are bolted onto the shelves where possible, preventing the relative movement of components.

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<sup>1</sup> Universal Serial Bus – provides peripheral connection to the host PC

<sup>2</sup> Local Area Network – provides a network connection between local devices on the AUV and surface machines

### **Frame**

The hull is contained within an aluminium frame and fibreglass shell. The use of aluminium reduces the overall weight while still providing enough strength to support the weight of the AUV. Accessories are bolted to the frame using stainless steel bolts. Sacrificial zinc anodes protect the metal components from oxidation in sea water.

The frame is the exoskeleton of the AUV, holding not only the main hull but also all the “life systems” of the AUV: the motors; the sensors; the air system and the marker dropper. The components can be quickly removed or attached to different elements of the frame as necessary, thanks to the modular nature of the frame and attachment methods.

The shell provides structural strength to the frame, and serves as a mounting surface for buoyancy foam.

### **Buoyancy and Air Pressure**

As in previous years, the *Hawthorne 2.0* relies on a SCUBA tank to provide positive internal pressure within the hull and components. Seals have been upgraded throughout the machine, but the air pressure system remains as a back-up to ensure the craft can function safely at the 20-30m working depths that will be required of it post-competition. Air from a SCUBA tank is fed through a high pressure SCUBA hose to a regulator and then through low pressure PE tubes to the hull and to every component box. The SCUBA regulator, which is mounted low on the frame, maintains the internal pressure of the AUV at slightly above ambient. On surfacing, a diver’s dry suit dump valve releases excess air pressure into the environment. A further advantage of this system is provided to the hull design constraints. In an unpressurised hull, when diving, the hull must be designed to be strong enough to withstand the increased hydrostatic pressure. However, by maintaining the internal to external pressure differential close to zero, we have been able to use inexpensive, rectangular IP67 boxes to house external components.

The hysteresis in the system, noticeable when ascending, does however preclude the use of an internal pressure sensor to accurately sense depth. An external pressure sensor is used instead. An internal air pressure sensor is nonetheless included to verify that the pressure inside the hull is being maintained above the ambient pressure. If the differential goes negative, an emergency surfacing subroutine is initiated in the control code.

The submersible is passively buoyant, in accordance with the rules of the SAUC-E, but the absolute value of the buoyancy will change, increasing over time. This is because the weight of the *Hawthorne 2.0* reduces over time as the air in the SCUBA tank is used.

At present a 2 litre internal volume steel SCUBA tank is used. When filled to capacity at 20°C to a pressure of 220 bar this tank will hold approximately 220 litres of air. Based on an air density of 11.81 N/m<sup>3</sup> at 20°C the mass of the contents (excluding the tank) will be:

$$\text{Density of air} = 1.204 \text{ kg m}^{-3} = 1.204 \text{ g l}^{-1}$$

$$2 \text{ litre tank @ 220 bar @ 20}^\circ\text{C} = 1.204 \times 220 = 264.88 \text{ g}$$

$$\text{Assume tank empties by } 1/3 \quad \frac{2}{3} \times 264.88 = 176.59 \text{ g remaining}$$

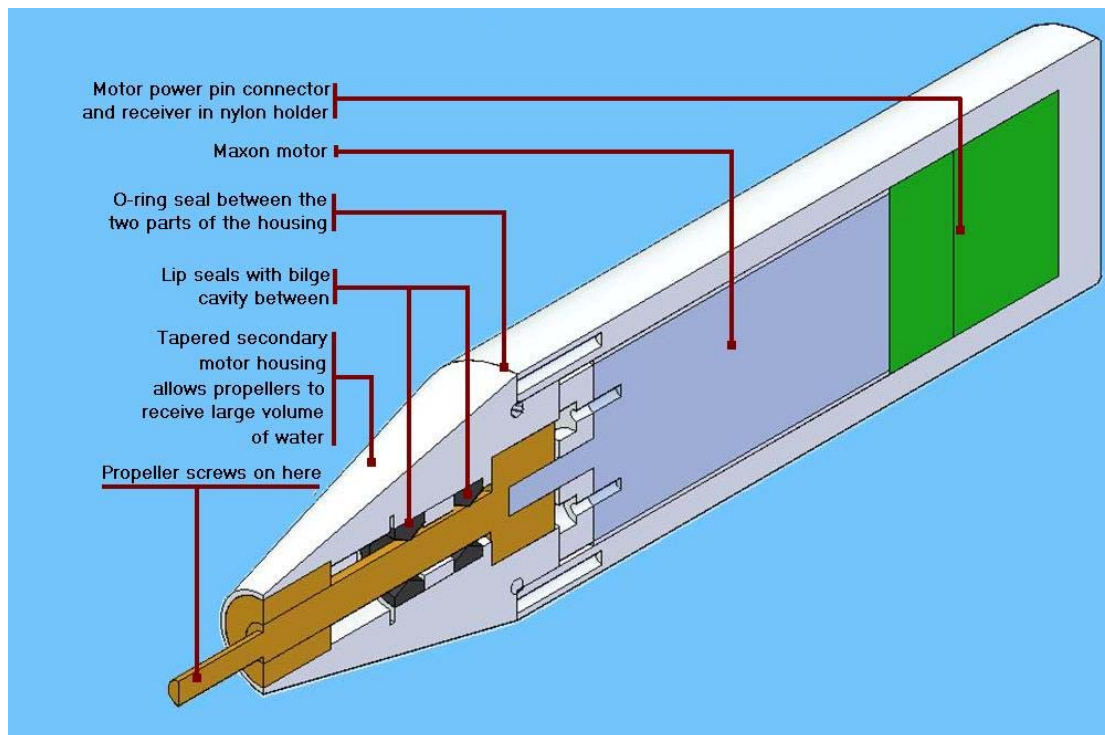
The buoyancy of the AUV will be trimmed to provide slightly positive buoyancy when the air tank is full. As the air tank reduces in weight by approximately 88 grams over a one hour session, the vertical motors will be able to automatically compensate for the change in buoyancy.

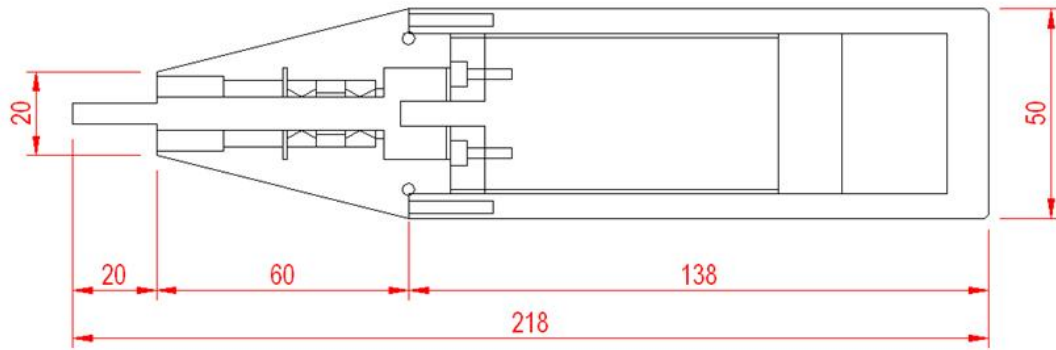
The air system is one example of the design for service (life post-competition) philosophy that has been adopted by the team. The air pressure system has been tested in the open ocean to a depth of ~20 m where other sealing methods might have failed. This will therefore enable the *Hawthorne 2.0* to operate at all depths, throughout the Ifremer tank.

### ***Propulsion System***

The *Hawthorne 2-0* possesses six propeller units for propulsion: four for planar movements and two for depth control. The in-plane units are set at 45 ° to the fore-aft axis (as shown in Figure 1) allowing the four propeller units to effect holonomic motion in the horizontal plane (as described in the Innovation section below). The two vertical propeller units can move the AUV both up and down by running the motors in different directions. The vertical motors have the propellers facing downwards to allow the propellers to be submerged as much as possible as the AUV lifts out of the water. This enables a high buoyancy and therefore high waterline, for example to enable surface wireless transmission, whilst still allowing the AUV to dive below the surface. In addition, the propeller units are more efficient when the water enters the propeller through the nozzle and is accelerated out through the back of the nozzle and over the motor housing. The AUV is designed to be positively buoyant as a failsafe and so, because much of the time is spent driving the AUV downwards to counteract this buoyancy, the vertical propeller units are orientated to provide maximum efficiency when driving the AUV downwards. The propeller units are all the same, which reduces the number of spare parts needed and further strengthens the modularity of the design.

A propeller unit consists of a 70 mm brass, three-blade propeller attached to a high-torque Maxon 70W DC graphite brushed motor in a sealed aluminium housing, shown in section in Figure 2. The housings, essential for waterproofing the motors, consist of two main parts, bolted together and sealed with a compressed O-ring. With the correct manufacturing tolerances, we can be sure that the O-ring seal between the two sides of the housing is reliably waterproof, which leaves the lip seals around the shaft as the weakest points for water ingress.





**Figure 2 – Top: Section view of the motor housing  
Bottom: Dimensions of the housing**

To prevent water ingress around the rotating propeller shaft, two seals are used, with a bilge cavity between them. If the first lip seal fails, water can collect in the bilge and the second lip seal protects the motor. The second lip seal is less likely to fail as any bilge water will not exert the same hydrostatic pressure on it as the outside water: the two seals provide a more gradual pressure gradient between the wet side and the dry side. A saltwater switch in the bilge activates an alarm which will initiate an emergency surfacing subroutine in the control software. This careful design means the motor housings do not require the air supply needed by other component housings. Other features of the motor housing design include:

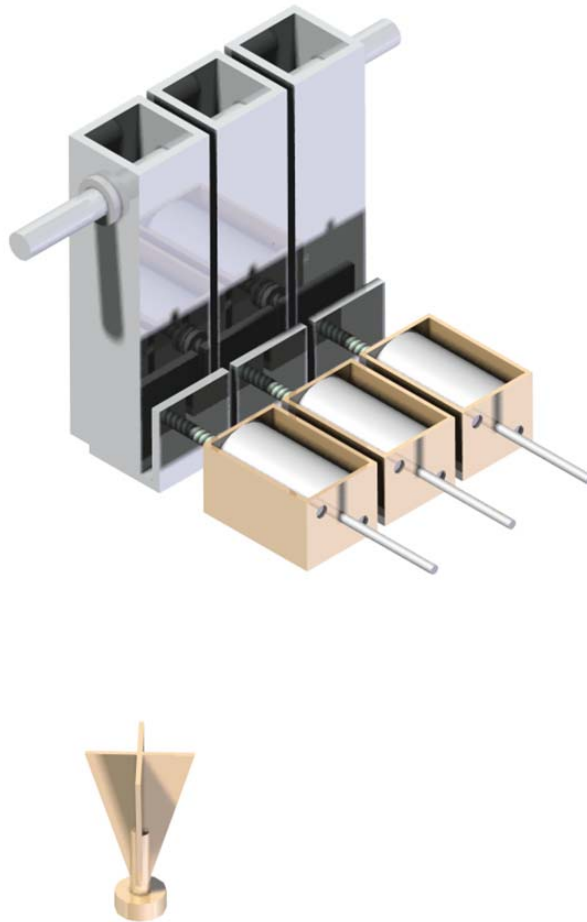
- Blind bore of primary motor housing ensures back end of housing is watertight and removes need for second O-ring
- Tapered secondary motor housing ensures propellers receive large volume of water intake for improved propulsion efficiency
- Bayonet plate on front of motor to rotationally lock the motor to the housing in fast, easy and reliable method
- Replaceable brass bushing pressed into aluminium housing to support long shaft adapter, and thus lip seals not damaged in supporting shaft
- Traxxas high-current connectors used to allow easy and reliable power connection from outside of motor housing to motor itself

The materials used to build the motor housings were selected to minimise the risk of corrosion, hence the use of aluminium, brass and stainless steel. However, since salt water is very corrosive, sacrificial zinc anodes will be bolted onto the submarine legs to reduce galvanic corrosion of the working parts.

Shrouding each propeller is a guard to conform to the competition regulations. The guards also provide a thrust augmentation by concentrating the flow aft. Each motor runs at approximately 1500 RPM but can be adjusted to run at any percentage of the top speed, and can produce 15N of thrust at top speed.

### ***Marker Dropper***

Underneath the main AUV hull is the marker-dropper mechanism. A frame holds three high force/stroke ratio miniature solenoids that operate a trapdoor mechanism. Each trapdoor holds a marker in a piece of 19 mm aluminium box section. The markers are released one at a time when the appropriate signal is passed to the solenoid from the computer. The markers are made from M8 bolts with flights slotted into a groove cut into the threaded end. Since the head of the bolt is heavier end, it always falls head first in the water. The flights help the bolt to keep a straight-line path. Observational tests show that even when there is disturbance on the water, the bolt falls in a straight line.



**Figure 3 - Marker dropper mechanism. Markers are contained within square sections of 19mm aluminium. The lower ends of the tubes are stopped with segments of 19mm L-section aluminium which are retracted by independent solenoids encased in a waterproof housing (not shown).**

The marker dropper was designed as an inexpensive module to be fitted to the *Hawthorne 2-0* for the SAUC-E. The total cost of the marker dropper unit was approximately £25.

## Sensors and Information Gathering

In order to respond to the underwater environment, an AUV must have knowledge about that environment. Sensors and cameras are used by the *Hawthorne 2-0* to gather information about external factors such as depth and heading, about objects around the AUV such as their shape and colour but also about internal factors such as temperature in the component housings.

### *Sonar*

A forward-facing multibeam sonar unit (Imagenex Delta-T) is mounted on bow of the AUV under the forward webcam. The sonar beam opens to  $3^\circ$  in the horizontal plane and  $120^\circ$  in the vertical. By having the largest part of the beam in the vertical direction, the sonar can pick up the edge of the tank where the floor meets the adjoining wall from a relatively high position in the water, which makes it easier for the *Hawthorne 2-0* to locate itself in the underwater environment. The sonar is also used for creating the map of the surrounding environment, more details of which are given in the Software: Mission Planning and High Level AI section.

### ***Pressure Sensor***

The external pressure sensor (Keller, PAA21SR, 0 - 2.5 bar absolute) is used to control the submerged depth of the AUV. Pressure readings in the open air, at the surface and at the bottom of our test pool were used to calibrate the depth adjustment program so that the returned value of pressure corresponds to a depth. This will have to be recalibrated for the salt water environment of the SAUC-E. In our case, an external pressure sensor is more accurate than one placed inside the hull since we have a continuous but not consistent overpressure in the hull.

### ***Webcams***

Vision is provided by two webcams (Logitech Quickcam Pro 5000): one forward facing for mid-water target recognition and the other downward facing for bottom target recognition. The cameras are placed in waterproof mounting boxes (Fibox Fex #1919182) that are connected to the air supply and bolted onto the aluminium frame of the AUV. The bottom facing webcam is placed as close to the marker dropper as possible in order to minimise marker position errors. Webcams that have inbuilt pan and tilt functions were deemed too complicated and unreliable for our application. Having a bottom facing webcam rather than a tilting one is also more advantageous for the tasks that the *Hawthorne 2-0* will undertake whilst operating as a research vessel in the ocean.

### ***Machine Health Sensors***

Increased internal pressure and elevated temperatures have adverse effects on the electrical components inside the AUV. To track these adverse operating conditions, thermistors have been incorporated into the motor pods and monitored by a data acquisition system on the main computer. The machine health subroutines also monitor CPU temperature of the two motherboards, along with battery voltage level, current, water ingress, tank air pressure, and the pressure differential between the internal and ambient pressure. Critical levels for all sensors have been set, and if these are violated, an emergency surfacing subroutine is implemented in the control code.

## **Electronic Systems**

### ***Power***

The AUV carries an onboard battery pack to allow autonomous untethered operation, as well as having the capability of operating from a shore power source connected to the AUV via a tether. In this mode, the batteries can be used as a buffer (allowing a lower rated cable to be used) or the batteries can provide standby power which becomes available when the tether is disconnected. This also saves time during testing as the batteries can be charged *in situ*.

The submarine will use two battery boxes: one housing the batteries that power the motors only; and the other, housing the batteries which power the computers and sensors. This provides benefits in two ways. Electrical noise spikes and voltage droops, caused by switching the high-current motors, are isolated from the sensitive logic circuits. In addition, the relatively low power consumption computers and sensors can be powered for a relatively long time with a small battery pack, and under heavy use, the large and bulky motor battery pack can be easily swapped to give an extended runtime without adding size, weight and requiring a computer reboot.

For reliability and cost reasons, SLA (Sealed Lead Acid) batteries were selected over more exotic battery chemistries to power the AUV. In future designs, if greater funds become available, the size and weight of the AUV can be greatly reduced with the use of higher energy density batteries, such as Lithium-Polymer cells.

The power consumptions used to specify the AUV batteries are listed below. These figures were averaged over several testing sessions.

Component:	Current consumption @ 24V nominal:	Required runtime:	Battery capacity required @ 24V:
Computers & Sensors	2.5A	1h30	3.75Ah
Motors	30A (6 motors, 50% power)	0h20	12Ah

The battery pack to supply the computers and sensors is specified for 1h30 to allow for a 15 minute buffer on either side of the competition run, thus allowing time for preparation and time for downloading mission data / telemetry information.

The battery pack to supply the motors is specified for the motors running at 50% power (a conservative estimate) and only requires a runtime of 20 minutes. This keeps the size and weight down, whilst longer runtimes are permitted by hot-swappable battery packs.

### ***Computers and Sensors Batteries***

Two 12V 4Ah SLA batteries are connected in series to provide the required 24V, whilst providing ample capacity. The model is Yuasa NP4.0-12. These batteries will comfortably fit into a standard available off-the-shelf Fibox waterproof container, specifically the Fibox Fex 191918T model. This battery box will also double up as the front-facing webcam box, and since these batteries are lightweight, the stability of the AUV in pitching will not be destroyed.

The six motors have a much higher power consumption than the computers and sensors as shown in the above table. If enough sealed lead acid batteries were used to provide a constant run time for the hour long session, then the large size and heavy weight of the battery pack would become unacceptable.

Therefore two Yuasa NP12-12 were selected to provide 24V 12Ah (144Wh) when connected in series giving over 20 minutes propeller time. A spare charged pack of batteries can be easily interchanged in place of the discharged ones. In order to ensure a quick and smooth changeover of the batteries, a bought-in Peli box is used, which is rated as waterproof down to 100ft. The Peli case has one side hinged and the other side has catches to lock down the lid. During battery changeover, the diver simply slides the Peli case off the bottom of the submarine, opens the case and swaps the batteries over. A quick swappable reverse-polarity protected high-current connector is used to aid quick and easy changeovers. It is felt that over 20 minutes of propeller time gives the submarine enough time to have a good chance of completing all the tasks.

### ***Computers***

The *Hawthorne 2.0* possesses two computers, as detailed below. The tasks are split between two computers due to the high processor usage of the vision code. The vision is run on the computer with the faster processor but this comes at the cost of having a larger form factor and greater power consumption. Both boards use solid state hard drives for reliability (mitigation of humidity, condensation, pressure changes, vibrations, shocks) and for performance.

Computer	VIA EPIA EN-Series Mini-ITX Board	VIA EPIA PX-Series Pico-ITX Board
HD type	Solid state	Solid state
Processor speed	1.5 GHz processor	1.0 GHz
RAM	1 Gb	1 Gb
Task allocation	Vision code	Main control algorithms
Form factor	170 x 170 mm	100 x 72 mm
System monitoring	CPU temperature reading voltage monitoring	CPU temperature reading (manufacturing option)

## **Software: Low Level Code**

### ***Vision Code***

Since colour is a factor by which objects in this competition can be discriminated, a vision system is essential. An AUV in the SAUC-E must be capable of colour recognition but shape recognition and classification and 3D object recognition are useful capabilities for the AUV to have too.

C has been chosen as the main language since the OpenCV library, which already contains many of the appropriate filters and algorithms, is implemented in C/C++. This reduces the time needed to create programs for the vision system.

### **Locating the buoy**

In order to find the buoy, a sample colour is needed. In the underwater environment, colour changes significantly with distance, and so an eigenmodel was built about the sample colour. This means that colour classification is robust against the changes that distance will introduce. Each colour is treated as a point in a multi-dimensional space, and in order to classify a colour, the Mahalanobis distance is calculated to decide whether a given colour is the target colour. If the distance is small enough, that colour is added to the eigenmodel, thus the model evolves and can learn new shades belonging to a colour group.

It is likely that the buoy will not be visible in every frame of the video stream and in this case it is important that the vision code continues to pass information to the other systems. It is necessary to track the moving buoy but also to predict where it will be when the visual track is lost. For this task, a Kalman filter, which is a general error tracking and linear function approximation algorithm, is used. The filter can predict locations when the vision is unsure but will allow the vision to correct the filter when it is sure. 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.

### **Locating the flashing beacon**

As the beacon will be the brightest object in the frame a simple brightness threshold is set and the frame is segmented based on the brightness of each pixel. For each potential position, the tracking algorithm (as above) is used. As an extra test, the shape classification described below is used based on the prediction that the flash will appear as a circular patch of light in the frame. In order to check whether the beacon is flashing, the vision code uses a frame buffer of 15 images and calculates the percentage of frames in which the LED is seen. If it is more than approximately 50 %, the beacon light is taken to be solid not flashing.

### **3D object recognition**

The cone and tyre task requires the use of the shape recognition and colour recognition algorithms together. We give the algorithm a series of training shapes, so that the algorithm can learn about the shape's form factor, roundness, aspect ratio, convexity, solidity and compactness. The Fourier descriptor, (components of a shape's "signature") is also calculated for the shape. The colour recognition is used to find the target and the shape recognition algorithm is used to identify it.

## Software: Mission Planning and High Level AI

Here we look at how the AUV is controlled in ROV mode, how the missions are planned and the autonomy: how the Hawthorne 2-0 decides which mission to attempt and how it executes them.

### LabVIEW GUI

All AUVs must have some ROV capability, if only for developmental testing, and the *Hawthorne 2-0* is no exception, especially since its future operations will be as an inspection class ROV. For this reason, a suitable graphical user interface (GUI) has been created in LabVIEW to control the *Hawthorne 2.0*. The GUI has links to the routines that make up the missions, as well as links to direct controls such as percentage power to each motor. From here the submersible can be directly controlled or it can be set to execute one of its routines (see following section for more on routines). The GUI also includes indicators such as remaining battery power, depth and internal pressure, these can be compared with target values to show how well the *Hawthorne 2-0* is performing.

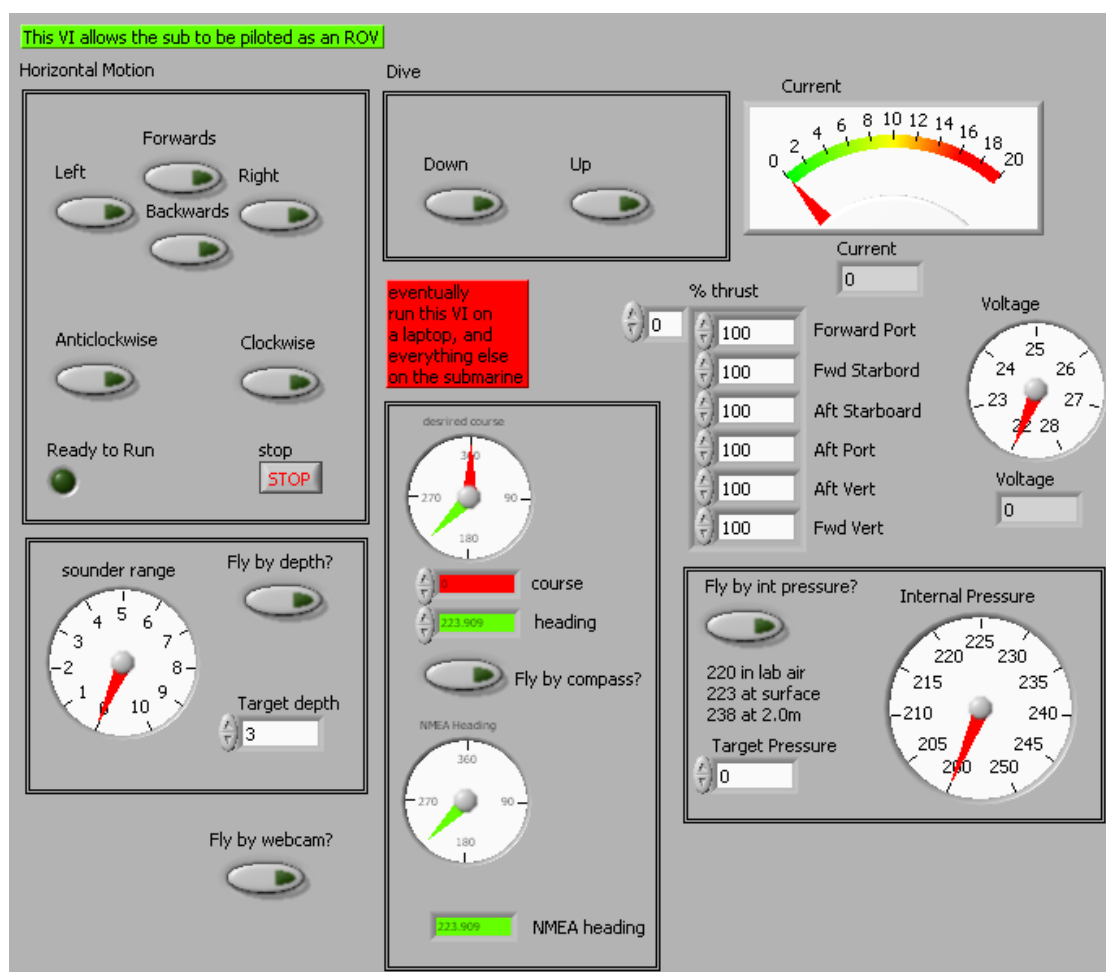


Figure 4 – Screenshot of the LabVIEW GUI

### Autonomous Movement Routines

There are three methods of autonomous movement. Each provides movement in a target direction based on readings from a specific sensor. These three movements are very similar in principle, the difference being the sensor (the compass, the pressure sensor, and the forward/downward facing webcams) and the corrective action taken in each case. These three subroutines provide 'fly-by-compass', 'fly-by-depth' and 'fly-by-webcam' functionality.

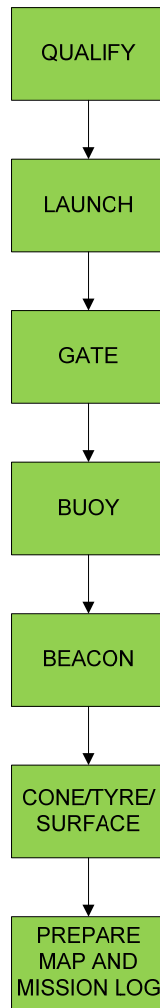
The general principle of movement relies on comparing the target direction with the current direction and, if the target differs from the current by more than a threshold value, then the movement is corrected back towards the target direction. This threshold value prevents the AUV from continually correcting at the expense of performance and also avoids the fast dynamic response of the hull from causing a large over correction.

At a later stage, proportional control can be added to provide a quicker and more precise correction to the movement. However at the current stage of development, incremental control is used – i.e. the control code iterates continuously through a process, comparing the target movement to the current movement and if the threshold is exceeded, changing the movement profile by a single step in the new direction.

### ***Operations***

Mission planning describes all the details involved with attempting the tasks set by the SAUC-E judges. Most intelligent behaviour, even in humans, is based on prior knowledge not real time searching. For this reason, the AUV needs precise instructions, of not just how to attempt a particular mission, but also *when* to attempt it. The overall structure of the mission plan can be seen in the flowchart in Figure 5 and a detailed representation of the mission plan can be seen in Appendix A. The high level control of the AUV is based on a hierarchical structure of objects and the individual blocks of the flow chart represent sub-VIs (virtual instruments) in the LabVIEW code, which perform different sub-tasks. The principle of each sub-task usually depends on executing an action once preset conditions are met.

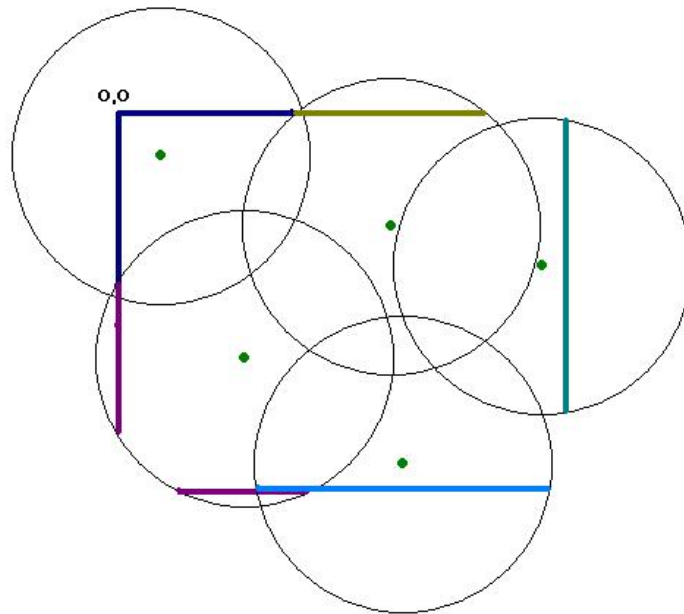
This hierarchical structure and modular code not only allows robust development and testing of individual parts as the overall task is gradually assembled, but it also allows flexibility in the way the overall AUV mission is planned and executed.



**Figure 5 – High level mission plan**

***Mapping of the Underwater Environment***

Once the *Hawthorne 2.0* knows where an object is relative to itself using the vision system, it will perform a 360 ° sweep of the tank. The sonar and the compass will create a map of the pool with the AUV at the position of the object. A final map will be created from superimposed maps of the pool with the position of the AUV each time marking the position of an object. Figure 6 shows a figurative representation of the combined map for objects located in 2D space. The AUV's mission log will be used to determine which object was found in which position and at what depth. Extra information such as the battery voltage and internal temperatures will be included in the mission log.



• object locations

**Figure 6 – How a map might be created of a 2D pool by reconstructing individual maps. Here the small green dots represent the found object locations, the black circles represent the limit of the sonar beam and the coloured lines represent lines found by the sonar that are the edges of the tank. The top left hand corner is selected at the origin.**

## Innovation

The *Hawthorne 2.0* is intended to be a major improvement on last year's boat. The design has not changed much and so the innovative features that were present in the original *Hawthorne* remain present. This year's big hardware improvements are coming in the form of upgrades to all of the internal components, including new pico motherboards and solid state hard drives, a switch to 24V, improved motor casings and seals, improved pressure sensing, and machine health sensors. Software improvements include complete reworking of the higher-level control code, some real innovation in the vision software, and mapping code based on a profiling multibeam sonar. As in previous years, we believe that what makes our boat stand out is its design for post-competition use.

### *Holonomic Movement*

The *Hawthorne 2.0* possesses high level in-plane manoeuvring capabilities. With four off axis propeller units, the AUV can translate and rotate very well in the horizontal plane. This is perhaps not so remarkable but the *Hawthorne 2.0* can achieve this with the direction of movement and the heading de-coupled. For an inspection and survey class vehicle this has great benefits for sensing; single directional sensors, such as vision and sonar units, can be mounted on the front of the vehicle. 360° scans can be undertaken whilst stationary by rotating on the spot, and also while underway by following a course while independently changing the yaw angle of the AUV. It also allows inspection of an area whilst the AUV is in transit, allowing directional sensors to remain focused on an area, despite a translational movement.

Plans for future AUVs include making the propulsions truly holonomic so that the shortest path between two points in 3D will be automatically taken by the AUV, rather than being constrained to series of orthogonal manoeuvres.

Thanks to the arrangement of propeller units with each at an angle of 90° to the other, the *Hawthorne 2-0* is able to turn on its axis and uses this to its advantage: objects are searched for by performing a full 360° sweep, using the sonar and vision to identify the presence of objects.

### ***Vision Code***

Due to mechanical difficulties in previous years, the BURST team has not been able to show how well the vision code can perform. Using a combination of algorithms previously developed for the SAUC-E and new code, we are confident that our vision system is not only novel but that it is well adapted to the SAUC-E tasks. In particular the object tracking algorithm, for finding the objects when they are not in a particular image frame, is new to the *Hawthorne 2-0* vision code. We believe it represents a simple yet very effective method to stop the AUV departing from its tasks.

### ***Lifetime Design***

One of the major design inspirations for the *Hawthorne 2-0* has been the operations after the competition. Previous BURST entries have been put to use searching for mysid shrimp in the Pacific Ocean off the West Coast of Canada (Figure 7). Any vehicle that is designed to be good at a number of tasks will never be a specialist in any of those tasks but this is no bad thing – the SAUC-E deliberately tests a number of different competencies that require different skills. The specifications for the vehicle that goes to Canada are different to those necessary for the SAUC-E vehicle, so the BURST AUVs have always been designed to be modular. For example, much effort has been put into the GUI for when the *Hawthorne 2-0* is operating in ROV mode. It allows the user to precisely control the *Hawthorne 2-0* or to switch on certain “autopilot” functions as the user sees fit. Another example of design for wider applications is the air pressure system. In the SAUC-E, this seems an unnecessary complication but in the ocean, at 20 m depth, seals that are within the budget of the ecology team using the *Hawthorne 2-0* would fail. This is partly due to the increased pressure but the lower temperatures also have to be considered.



**Figure 7 – The Hawthorne being deployed into the open Pacific from a fish boat in western Canada. The racehorse AUV turned workhorse ROV was used for ecological research on mysid crustaceans, which required it to dive repetitively to depths of 20m.**

The BURST AUVs have helped ecologists in Canada complete their work and they in turn have allowed the BURST vehicles to be tested in a unique environment. Thanks to their work, we know the physical aspects of the *Hawthorne 2-0* are safe at 20 m depth, at temperatures as low as 9 °C, and in salt water – an important factor for this year’s competition.

## Financial summary

We have been fortunate to be able to re-use many of the components from previous SAUC-E entries; however, the AUV has required maintenance and some new components. Here we detail components bought for this year's competition and the team's income, which has mainly come through sponsorship. We are very grateful to the Founders complex for allowing BURST to use the 25 m pool free of charge.

### *BURST (AUV) Income*

<b>Company</b>	<b>Type</b>	<b>Notes</b>	<b>Total GBP</b>
SEACON Europe	Parts donation	ALL-WET™/WET-CON series of connectors: 2 off BH-2-MP Stainless Steel 2 off IL-2-FS Inline connectors 1 off DC-2-FS Female blanking connector 3 off DLSA-FR Female locking sleeve 2 off DLSA-MR Male locking sleeve	-
BMTdsl	Money		500
BURST	Money	Cake sale	120
	Money	Earned from filming	100
<b>Total</b>			<b>720</b>

### *BURST (AUV) Spending*

<b>Part category</b>	<b>Amount spent GBP</b>
Batteries	214.35
Component boxes	121.33
Computer hardware	1036.27
Connectors	20.92
Electrical components	250.74
Materials	54.40
Miscellaneous	280.45
Motors	141.00
Seals	48.20
Sensors	429.41
<b>Total</b>	<b>2598</b>

The result of our financial summary is that the BURSTAUV team is in debt to the amount of £1878. The final accounting has not yet been completed, so this number may change between the date of writing and the competition.

## Risk Assessment

Here we include a *Hawthorne 2-0* design-specific risk assessment as well as our general submarine team risk assessment that has implications for our behaviour at the SAUC-E.

1 Name	2 Hazard	3 Who could be harmed?	4 How could they be harmed?	5 Risk before controls implemented			6 Control measures needed to minimise risk			7 Risk after controls implemented		
				L	C	LxC	Technical	Procedural	Behavioural	L	C	LxC
<b>Design</b>												
Body	Sharp edges on hull/frame	People handling the AUV	Cuts, grazes, general injury	2	2	4	Sharp edges filed down/removed	Team briefed on where potential hazards are, people not familiar with AUV warned	Lift only from designated points, only handle AUV when necessary	1	2	2
Batteries	Electric shock due to batteries	Anyone immediately involved, particularly those near the accident site, esp. if in the water	Particularly a problem with the 24V circuits in the AUV	2	3	6	Live battery connections insulated so shorting not possible; wiring properly insulated	Proper training provided	No metal tools near battery terminals	1	3	3

Batteries	Battery explodes due to gas build up	Anyone in the close vicinity of the battery box.	Burns, cuts, serious injury	2	4	8	Dedicated charger prevents overcharging	Team made aware of potential risk	No charging of battery without venting of gases	1	4	4
Batteries	Fire	Anyone near the battery	Burns	2	3	6	Fuses to prevent exceeding current rating of batteries and wiring, all connections insulated, reverse polarity protection	Check fuse values	Follow procedures	1	3	3
Propellers	Tangling	Anyone near running propeller	Cuts, injury	2	3	6	Shroud around propeller to mitigate	AUV users/handlers made aware of risks	No loose clothing/long hair near propellers when running	1	3	3
General pool hazards	Falls	Anyone	Mechanical injury	2	3	6	Non slip footwear to be worn	Initial safety briefing; all staff & students to familiarise themselves with pool rules, and these to be followed;	Lifeguard present at all times; caution to be exercised by participants; lifesaving training to be provided	1	3	3

General pool hazards	Drowning	Anyone	Drowning	2	5	10	Non slip footwear to be worn	Initial safety briefing; all staff & students to familiarise themselves with pool rules, and these to be followed;	Lifeguard present at all times; caution to be exercised by participants; lifesaving training to be provided	1	5	5
Excitement, time pressure	Lots of ways	Anyone	Judgement errors leading to accidents	4	1	4	Careful design	Careful planning, realistic goals & timelines, allow lots of 'flat tyre time'	Take it easy, stop and think	2	1	2
<b>Transport</b>												
Carrying the sub to pool	Slips, falls & strains	Those involved in carrying, bystanders	Mechanical injury	2	2	4	AUV designed to fit easily through doors; support carriages designed to take weight	Proper numbers of personnel involved when carrying	Take it slowly, use mechanical aids where appropriate; extra care along pool side	1	2	2
Assembly, final adjustments to the sub at pool's edge	Slips & falls; workshop injuries	Those working on the sub	Mechanical injury	2	2	4	Standardised parts; design for assembly/repair	Ensure sufficient working space around subs, away from water's edge. Use of scuba boots to prevent foot injuries from falling tools.	Take it slowly, methodically; ensure sufficient time so no pressure; use correct tools	1	2	2

Launching/retrieving the sub	Twisting, crushing injuries	Those working on the sub	Mechanical injury	2	3	6	Weight of subs kept to minimum; ergonomic grips in place;	All personnel trained in how to launch safely. Suitable numbers of people in and out of pool to pass sub between	Extra care; no overexertion; sufficient personnel available to reduce individual loads	1	3	3
<b>Testing</b>												
Spinning propeller	Mechanical injury (cuts, breaks, crushing)	Person handling the AUV	Sticking fingers into props, particularly to kick start/dejam them	2	2	4	Propeller guards installed; propeller tips painted orange; immobiliser for chain in hp sub	Communication between operator and support divers	Do not poke fingers into props!	1	2	2
<b>Electricity</b>												
Portable electric equipment (esp. computers, DAQ trolley) near water's edge	Electric shock, loss of data, damage to equipment	Anyone immediately involved, esp. those in the water	Equipment splashed, knocked into water	2	3	6	Where possible, portable poolside equipment to be battery operated only	Limited people to be involved with trolley	Extra care walking at pool's edge	1	3	3

## Appendix A – Detailed Mission Plan

