An Autonomous Sailing Robot for Ocean Observation

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An Autonomous Sailing Robot for Ocean Observation

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Abstract

The introduction of the Water Framework Directive has highlighted the need for water quality monitoring in freshwater systems, estuaries and at sea. Systems which currently exist for these tasks include fixed monitoring stations, both moored and drifting databuoys, survey ships and satellites. Moored databuoys suffer from significant costs in their deployment and maintenance, floating buoys are often lost, survey ships can only cover limited areas while satellites take years to manufacture at vast expense and lack the resolution and accuracy of in-situ devices. It is therefore proposed that a small autonomous sailing boat could be used to complement these systems. Such a boat can either be instructed to hold a fixed position by constantly circling or sail a predefined course such as crossing an ocean. Currently two 1.5m long prototypes have been developed and tested on lakes and coastal waters. They are propelled using a solid wing shaped sail. Electricity for use in sail and rudder control motors is provided by onboard batteries. A wind sensor, GPS and compass provide data to a computer which controls the rudder and sail positions. In order to successfully survive at sea for long periods of time it is envisaged that in addition to high quality hardware there will be a requirement for software which can balance competing interests particularly upon the electrical systems. Work is taking place to model such a system upon homeostasis within biological systems.

1. Introduction

Autonomous robots have been successfully demonstrated in a number of applications, including planetary and underwater exploration. Despite this success, little attention has been focused on the development of Autonomous Surface Craft (ASCs). Development of such craft to date has focused mainly on short-range craft powered by electric or internal combustion engines, such as those developed for the Texas Coastal Observation Network (TCON) (Steidley and Backnak, 2004). Such craft are significantly limited in range and endurance due to their need to carry the required fuel onboard or gain it from their environment, usually through solar panels. A potential method to overcome these limitations is to employ a sail to propel the vessel eliminating the need to carry fuel or batteries to power a motor for this purpose. A sailing vessel will only require minimal electrical power to adjust its control surfaces and power onboard computers. Sufficient power to run the electrical system can most likely be gained from photovoltaic cells, allowing such a robot to become completely power autonomous and therefore operate continuously for months at a time in the middle of an ocean.

It is envisaged that the primary role of such robots will be in performing in-situ monitoring of ocean conditions such as temperature and salinity. This task is currently performed via a combination of in-situ monitoring devices such as moored and drifting data buoys or survey vessels and remote monitoring systems such as satellites and aircraft. It is generally accepted that in-situ systems are capable of providing higher resolution data (Legrand et al., 2003) than remote methods, they are also capable of taking sub-surface measurements which remote systems are generally unable to do. However each in-situ device is only able to sample a single geographic location therefore vast numbers of devices are needed to cover a large area requiring each one to be reasonable cheap while also being robust enough to survive unattended for long periods of time.

Given their relatively low cost in comparison to satellites and survey vessels it is envisaged that large numbers of sailing robots could be deployed in a grid. Each boat would hold a fixed position (to within approximately 100m) by constantly circling a given point or by heaving to [1]. Should the shape of the grid need to be reconfig-

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[1] A sailing manoeuvre which places the rudder and sails of a

ured when a boat returns for repairs then other boats would be able to manoeuvre themselves to maintain the grid pattern without the need for ships to pick them up. It is envisaged that boats can be deployed and retrieved in sheltered coastal areas and make their way autonomously to and from their destination. This ability greatly reduces the operational cost in comparison to data buoys which require regular maintenance visits from manned repair vessels and must be deployed on location in the open sea. It is also possible that boats can sail long distance pre-determined courses (such as crossing an ocean) filling the role of a survey vessel.

Several previous attempts have been undertaken to construct sailing robots most notably (Abril and Calvo, 1997) and (Ross, 1998). Both of these attempted to convert existing model boats into sailing robots and were able to demonstrate basic working control systems. Unfortunately neither appears to have followed up their work with any attempt to launch boats into the open sea or to address the problems of constructing boats to survive such an environment.

2. Possible Designs for a Sailing Robot

2.1 Hull Desgins

Several possible hull designs exist for an autonomous sailing boat. An ideal hull would be cheap to manufacture, able to self-right in the event of capsize, small enough to allow for easy transportation and to prevent damage to another vessel in the event of a collision but large enough to be able to sail effectively in heavy seas. Additionally any such hull needs to be fully enclosed to prevent water entering the hull, eliminating the need for costly pumps to remove excess water.

The first possibility is to use a hull intended for radio controlled model boats (under 3m long), such hulls tend to be fully enclosed, cheap, easy to transport and unlikely to cause damage to other vessels however they are likely to struggle in heavy seas and are generally not capable of self righting. Another possibility is that of a small dinghy hull (3-5m long) which although significantly more expensive than a model boat hull is capable of being transported with an ordinary car and should be more capable of sailing in heavy seas. Sailing dinghies are not typically self righting and usually require the crew to remove water from within the boat without the aid of pumping equipment. Significant modification to the hull would be required in order to overcome these issues. The final option is to modify a yacht sized hull (5m+ long), this approach presents the best candidate for coping with large waves. However significant expense would be required to enclose the cockpit and specialist vehicles may be required for transportation. Such a hull would also be of the greatest danger to other vessels in the event of a collision. Given these options the best design would appear to be a large model boat style hull as it is relatively easy to modify such a hull in order to create a self-righting design.

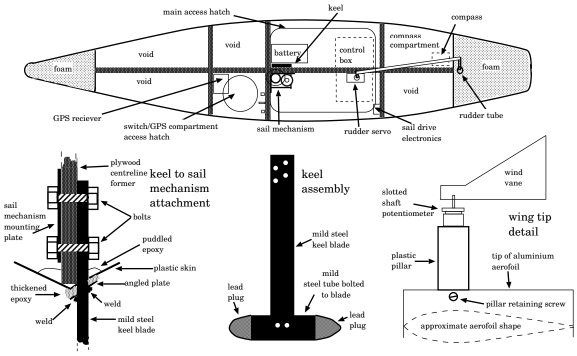

Figure 1: Details of the general construction (Neal, 2006)

2.2 Sail Designs

The other key factor which must be considered in designing such a vessel is that of the sail type. Traditional fabric sails are typically controlled through a series of ropes known as sheets and halliard's, these frequently break or jam (particularly when swollen by salt water) and require regular attention from the crew. Performing such tasks autonomously would incur significant overheads resulting in excessive power usage, weight and financial cost. A potential alternative is that of a rigid wing shaped sail attached directly to the mast (somewhat similar to a windsurfer sail). The sail is manipulated through the rotation of the entire mast via an electric motor. This design eliminates common points of failure found in traditional sails and is therefore ideal for use in an autonomous sailing vessel.

It would also be highly desirable for the sail to be able to increase and decrease its size in order to reduce or increase the amount of force exerted upon it by the wind. This is similar to changing to a larger or smaller sail or reefing [2] in a traditional sailing boat.

3. Prototype Description

To date two small prototype boats have been constructed, both are approximately 1.5m long and make use of a wing sail rotated by an electric motor. Hulls of these dimensions were primarily chosen to allow the boat to be moved by a single person and to fit within an estate car for easy transport. It is appreciated that this hull size is not optimal for use in the open sea and

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boat in opposing positions that effectively cancel each other out causing the boat to remain stationary.

[2] A process by which the size of the sail is decreased by wrapping it around a boom.

that a larger hull would be more appropriate, however for development purposes this is impractical from both a logistical and a financial point of view. The first prototype features a hull constructed from ABS plastic, a single aluminium wing sail and a single rudder. The second features a hull constructed from plywood, dual acrylic wing sails and dual rudders.

3.1 The first prototype

3.1.1 Hardware

The first prototype was constructed in the winter of 2004/2005 and tested in spring 2005. It features a 1.5m long hull made from ABS plastic, a 1.3m high single aluminium wing sail, a single rudder, a 55cm deep keel with 3.5kg of lead ballast at its base. Power is provided through two 12V 4.2amp lead acid batteries, it is expected (but has not been tested) that they can provide up to 36 hours of operation each. The sail is controlled via an electric motor and the rudder via a servo. A potentiometer connected to a wind vane is located at the top of the mast in order to provide a wind direction sensor. A CMPS03 [3] magnetic compass provides a mechanism for basic navigation, a GPS receiver was placed onboard during testing to log the boat's position however it was not connected to the control system.

3.1.2 Control System

The control system consists of a Basic Stamp 2sx microcontroller [4] connected to the compass, wind sensor and the two motors. Given the limited processing power and memory available on the Basic Stamp, a PDA was connected via the serial port in order to run the (relatively) processor and memory intensive high level decision making code. To provide the PDA with access to sensor data and servo control a simple command protocol was established with the Basic Stamp providing access to the sensors and motors and the PDA performing control decisions. A Psion 5MX PDA was initially chosen as it featured a compact flash card for non-volatile data storage and was able to run the Linux operating system, this facilitated the development of software with a laptop PC also running Linux, with the code only being uploaded to the Psion once it had been proven to behave correctly using the laptop. This process dramatically reduced the time required to develop the software. However issues emerged where the program behaviour differed between the laptop and the Psion due to compiler differences.

A number of shortcomings were identified in the use of a control system split between a PDA and a Basic Stamp. These mainly concerned the speed at which the Basic Stamp could handle incoming commands from the PDA, as a result of this problem the Basic Stamp would occasionally crash if insufficient time was left between two commands. The initial choice of a Psion 5MX PDA created additional hardware problems as in placing the Psion into the hull of the boat often knocked its rather flimsy serial connector out of position. To resolve this it was later replaced with an HP Jornada 720 PDA (also running Linux) which featured a more robust connector and offered the facility of a wireless network card which simplified reprogramming and data transfer.

To ease the development of the control software a simulator (based upon an open source sailing game [5]) was implemented to present the same API as the robot control program. The simulator allowed the basic behaviour of the control algorithms to be verified, however the simulator proved to be of only limited use as it was too perfect often reacting faster than the real robot could and failing to simulate many of the problems encountered in the real world.

The control system was implemented in the form of a simple proportional controller that enabled the boat to remain on a compass heading specified by the user at run time. The proportional controller operated by making rudder adjustments in proportion to the difference between the current and desired compass heading. Sail adjustments were made through an algorithm which linked wind directions (relative to the boat) with appropriate sail settings via a lookup table. An additional complication to both these algorithms occurs due to the fact that sail powered vessels cannot be sailed directly towards the wind and are typically capable of sailing only approximately 45 degrees either side of it. A boat attempting to sail into the wind must therefore zig-zag across the wind in order to make any headway. This situation was detected by comparing the desired heading to the currently observed wind direction, when it was determined that the boat was in the 90 degree "dead zone" the desired heading was then adjusted to be 45 degrees more than the wind direction, after a pre-determined amount of time it was changed to be 45 degrees less than the wind direction and this process of alternation continued until the wind direction changes or the boat changes course.

3.1.3 Results

A series of test sailings were undertaken on a small inland lake in order to minimise the risk of losing the robot. The key aim of these tests was to test the ability of the control system to hold a pre-determined compass course and to test the ability of the hull/sail design to cope with different points of sail. Initial tests were performed with the aim of testing the sailing performance and feasibility of the chosen hull design. Later tests focused on the

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[3] http://www.robot-electronics.co.uk

[4] http://www.parallax.com

[5] http://tracksail.sourceforge.net

Figure 2: The first prototype leaving shore during a test run.

development of a software control system and its ability to maintain a pre-determined compass heading.

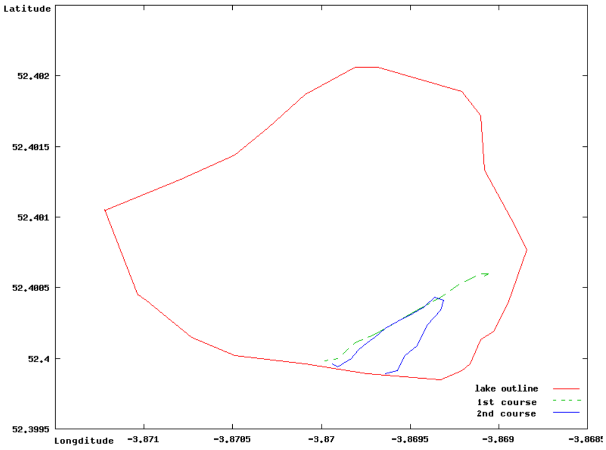

Figure 3: A GPS Plot showing the course taken by the first prototype boat in sailing across the lake and sailing halfway across and returning.

The sailing performance tests were primarily undertaken in the winter months when conditions at the test site were somewhat extreme with sustained wind speeds exceeding 30 km/h and wave heights exceeding 7cm in one case. Despite these conditions the hull remained stable and rarely heeled to an angle of more than 45 degrees. In cases where the angle exceed this the boat soon righted itself due to the ballast at the base of the keel. Although this is an encouraging start it remains to be seen if a boat of this size could survive wind speeds in excess of 100 km/h and wave heights in excess of 5m as would be expected upon the open sea. One flaw which was discovered during this testing was that the narrow and deep design of the keel resulted in excessively high manoeuvrability. This (when moving at a reasonable speed) resulted in turns in excess of 90 degrees occurring within a single boat length, during these turns the hull would typically heel to approximately 45 degrees. This issue was later believed to be partially responsible for a constant oscillation of the boat with respect to its target heading when operating under software control.

Due to issues in the sail movement the control system tests had to disable the automatic sailing positioning algorithm and operate using the course holding algorithm alone. The full reasons behind this are discussed in section 3.1.4. With the problems caused by the sail setting removed, a number of successful course holding tests took place. The boat was given a compass heading which was intended to take it across the lake over a distance of approximately 200m. Several successful crossings were made with the boat managing to maintain a roughly straight line figure 3 shows a plot from the onboard GPS receiver during one of these tests. It is worth noting that the system used by the GPS receiver to store its tracks compresses the data in a lossy manner removing the detail of many smaller movements which therefore are not visible in this figure.

The boat's rapid turning ability combined with a high proportional gain resulted in wild oscillations with respect to the heading during early tests. It is believed (although virtually impossible to accurately determine from the results gained) that these were in part due to the compass misreading headings as the boat heeled due to the action of the wind and due to the extreme turns it was taking. A reduction of the proportional gain reduced, but did not eliminate these oscillations.

A later experiment sailed the boat for 2 minutes on the compass course used in the first experiment, then moved the sail onto its opposite position and gave the course holding program the reverse heading to follow for an indefinite time period. The end result was that the the boat returned to near the point it had departed from. Figure 3 shows a GPS plot of this test. Note the amount of space it takes for the turn is not the time the boat actually spent turning, but is mostly the time it spent rotating the sail which also had the action of causing a turn in the correct direction to begin, during this time the boat was not attempting to perform any other control as there was no attempt at parallelism in the software being used.

3.1.4 Issues with this design

The use of standard electric motors was found to be inappropriate for sail control as the motor must be brought to rest for a period of time in order to allow momentum to be lost before the current sail position could be checked against the desired position. The sail rotation mechanism operated by employing a potentiometer to test if the sail was in the correct position. This mechanism was controlled via a 3 point controller which would rotate the sail a few degrees, compare the current position with the desired position and continue moving if it was not met. In many cases this resulted in an overshoot of the desired position which then required the sail to be rotated in the opposite direction. The end result was that sail movements became exceptionally time consuming (over 5 seconds). An attempt to overcome this through the use of a PID controller for the sail rotation was attempted. This resulted in a marginal improvement however the sail still frequently overshot due to the effects of momentum and the inaccuracy of the potentiometer being used.

Due to the nature of the control system implementation no other actions could take place during sail movement which resulted in the vast majority of processor time being spent waiting for sail movements to completed. This caused rudder actions to be left operating for too long essentially causing the robot to be unusable. Reasonable performance was only achieved by disabling the sail setting algorithm and leaving the sails set to a sensible default position. It was recognised that any future system would need to rotate the sail faster, less frequently and in parallel with other controls.

As discussed in the previous section it was believed that when the boat heeled to one side it introduced errors in to the compass heading which in turn caused the steering control to adjust the boats course. A boat intended for operation on the open sea will need to counteract this problem, one possible solution is to place the compass on gimbles to keep it level at all times.

3.2 The Second Prototype

A second prototype was constructed in Spring 2006 and attempted to address many of the issues discovered in the testing of the first. It is of similar dimensions to the first prototype, however the hull has been constructed from plywood and the sail from a lightweight plastic in order to reduce weight. A second sail has been added to improve sailing performance this has the added benefit of improving the boat's ability to sail in a straight line as single sail boats have a tendency to veer off course slightly. A dual rudder configuration has been employed to add redundancy, these rudders have also been angled slightly to allow the boat to list to one side while still keeping one of the rudders fully submerged in the water in order to improve steering ability in strong winds. The keel is approximately 20 cm deep, 20 cm long and 3 cm wide, approximately 5kgs of roofing lead is fixed to the base of the keel for additional ballast. Power is provided by 12 rechargeable NiMH AA batteries placed in the keel. These serve a dual purpose as ballast while providing a cheap and easily replaceable power source. The sail control mechanism has been changed from a standard motor to a stepper motor as the standard motor proved difficult to control resulting in it overshooting the desired position. The rudder control has been changed from a servo to a stepper motor in order to reduce power consumption. A GPS receiver has been added to allow for true point to point navigation requiring the user only to supply a list of waypoints, place the boat in the water and let it find its way between them. The compass and wind sensor from the first prototype were re-used however the compass was placed on a swinging arm to reduce the effects of tilt.

Figure 4: The second prototype.

3.2.1 The Control System

The control system has been completely redesigned and replaced with a system using an AT Mega 128 microcontroller and a gumstix single board computer running Linux. The gumstix currently provides short range radio communication via an 802.11 wireless network, its main purpose is to act as a wireless reprogramming system for the ATMega and to transmit telemetry information during sailing. It is intended in future that several microcontrollers will be employed, one controlling the sails, another controlling the rudder and a third managing the communications and navigation. These microcontrollers will perform all communication via I2C and it is envisaged that all sensors and actuators will be I2C devices allowing for a single microcontroller (or a pair of microcontrollers) to take over complete control of the system in the event of one or more failing. The potential also exists to provide redundant connections to each actuator and redundant sensors to increase fault tolerance.

3.2.2 Results

This prototype was entered into the 2006 Microt ransat Competition (Briere, 2006) held on a river near Toulouse, France during June 2006. In order to complete the competition the entrants were required to sail between a pre-determined set of GPS waypoints. This course included sailing both into the wind and downwind. Unfortunately a combination of exceptionally strong winds and hardware failure (of several teams) prevented the sail actuators from operating correctly. To

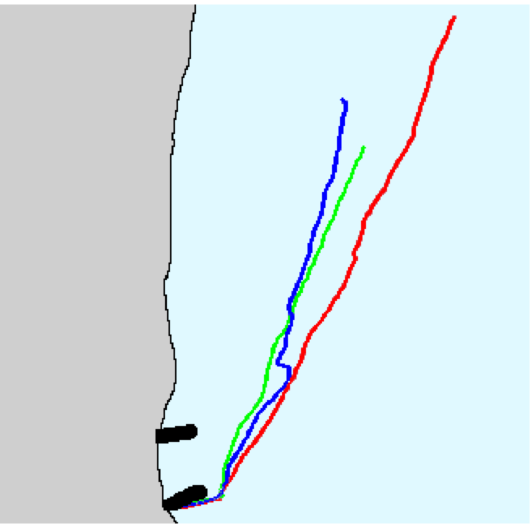

Figure 5: A map showing the routes taken by the boat during the 2006 Microtransat challenge. The kink in the middle path shows where the boat was pushed off course by the wake of a passing motor boat.

circumvent this and demonstrate that the robot was capable of sailing in such conditions the sails were tied in place and a basic course holding program was loaded. This was able to sail towards the desired heading in a reasonably straight line despite a strong river current, cross wind and the wash from passing motor boats. A total of three tests with identical parameters were performed and the actual courses followed are shown in figure 5.

To test the sailing stability of this robot a further experiment was undertaken in which the rudder was centred, the sails positioned appropriately and the control system turned off. The robot was then placed on the same course as in the previous experiments. The robot successfully sailed in a straight line and followed a course similar to those of the previous experiments. Even when forced off course by the wash from passing boats the effect of the dual sails caused a correction to take place. Such behaviour is ideal for a highly autonomous vessel as it allows the control system to remain inactive the majority of the time, reducing overall power consumption and improving autonomy.

A further attempt to sail this prototype in sea off Aberystwyth was later made. The intended course (shown in figure 6) was a triangular course requiring the boat to sail towards the wind, across the wind and down wind eventually returning to its start position. Successfully being able to sail a triangular course is considered important as its one method by which a boat could hold a fixed position (which would be at the centre of the triangle). Unfortunately the robot failed to reach its first waypoint due to a gear driving the sail coming loose and the software responsible for determining the heading to the next waypoint experienced a divide by zero due to the short distances between waypoints and the lack of precision in floating point numbers in the microcontroller. At the time of writing these issues have been resolved but there has been insufficient time to perform additional testing.

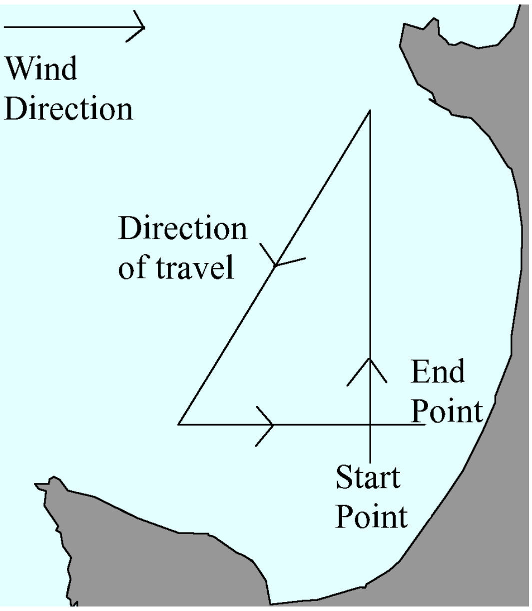

Figure 6: The route for the sailing tests off the coast of Aberystwyth.

3.2.3 *Issues with this design*

This prototype has proven to be able to sail with greater stability than the first, its control system is far more versatile giving it the ability to position sails and rudders simultaneously and navigate between GPS waypoints. However it is still not suitable to spend long periods of time at sea given its relatively small size and lack of any long term power source. One of the key lessons from its construction has been the need for a stable hull design which dramatically reduces the frequency of course correcting manoeuvres. Another lesson is that components which get hot such as power transistors need to be monitored and switched off before they cause damage to themselves and the rest of the robot.

3.3 *Future Work*

Funding has been secured to outsource construction of a larger prototype intended for long term use on the oceans.This prototype should be complete by the end of 2006. It will build further upon the lessons learnt in the testing of the current prototypes, in particular the inclusion of a series of proprioceptive sensors to monitor its internal state and the use of photovoltaic cells as theprimary source of power.

To further the development of autonomous sailing robots a competition (Briere, 2006) has been established to race boats from a number of competing organisations across the Atlantic Ocean during the summer of 2008 with shorter distance races taking place in the summers' of 2006 and 2007. The second prototype described in this paper took part in the 2006 race and will most likely be entered into the 2007 race. The races not only aim to boost the technology involved in autonomous sailing robots but also to boost their public perception both amongst the general public and the scientific community.

To be of any scientific use a sailing robot for ocean observation will need to include some kind of long distance telecommunications system as data needs to be transferred at regular intervals since there is no guarantee that the robot will be retrieved. It is intended that a satellite phone will be used for this purpose, spending only a few minutes each day transmitting its observations and receiving new instructions.

4. Legal Issues

The operation of autonomous vehicles at sea presents a number of legal issues. These mainly regard collisions with another vessel. Any manned vessel operating at sea must adhere to the International Rules for Prevention of Collisions at Sea (Organisation, 1972), these rules lay down procedures for avoiding collisions such as lighting and how two vessels should pass each other. Unfortunately no reference is currently made to autonomous vessels. The rules define a vessel as being a means of transporting people or goods, therefore it appears that a sailing robot may not be classified as a vessel and may enter classifications comparable with those of a buoy. Regardless of this status there are clear requirements for lighting to alert other vessels to stay clear. The present prototypes feature no such lighting and this must be considered for any boat being used on the open sea, this need to light the boat will also have an impact upon power requirements. (Showalter, 2004) has reviewed current US and International Laws with regards to Autonomous Underwater Vehicles (AUVs), although ASCs are not explicitly mentioned by Showalter a number of her findings are relevant as many AUVs spend some of their time above water. Showalter outlines several key problems for AUVs including causing harm to marine life, collision with another vessel, entanglement in a net and production of excessive noise from SONARs. Of these all but the latter are likely for a sailing robot (assuming it has no SONAR). Showalter concludes that there is currently a regulatory gap regarding AUVs but that this is likely to close with the growing use of AUVs. Hopefully any legislation (national or international) regarding AUVs will also be appropriate to cover ASCs.

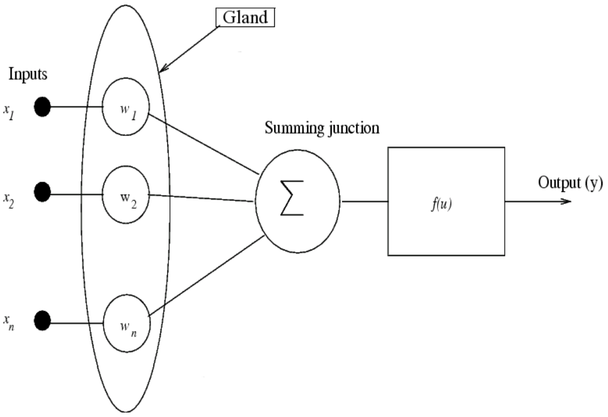

Figure 7: The modified ANN used in a neuro-endocrine controller. The gland is able to alter the weights of neural network.(Neal and Timmis, 2003)

5. Improving Survivability

A key requirement in producing a robot for practical use is that it be capable of preserving itself in the face of harsh conditions and adapting to failures of components. In order to remain of use to potential users it must also continue to perform its mission wherever possible in the face of these issues.

Biological organisms have proven themselves to be highly adaptable, able to sense and avoid danger and survive in harsh conditions such as extreme temperatures, malnutrition and dehydration. These capabilities are in part due to their ability to maintain a constant internal state in the face of a constantly changing external environment. This ability, known as homeostasis is largely controlled through the secretion of hormones from various glands collectively known as the endocrine system. The hormones released by this system act as messengers to other systems which cause them to modify their behaviour. A common example of this ability is the release of adrenaline in life-threatening situations in order to speed up reaction times of the brain.

It has been proposed (Neal and Timmis, 2003, Neal and Timmis, 2005, Henly, 2006) that artificial homeostasis within a robot can be achieved through the use of artificial glands which release behaviour modifying signals to other systems within a robot. (Neal and Timmis, 2003) and (Henly, 2006) have implemented a modified artificial neural network (ANN) in which a gland releases hormones which have the ability to modify the weights within an ANN and thus excite or suppress certain behaviours. Figure 7 illustrates this modified neural network.

It is proposed that several glands be implemented as part of an Artificial Endocrine System with these drawing from different sensor inputs and pieces of data currently held by the robot including sea state information, battery power levels, solar panel output voltages, internal temperature and humidity. Each gland would in turn be responsible for secreting different hormones each with their own effects upon the system. It would therefore be possible for several glands to secrete hormones simultaneously giving rise to new behaviours combinding the effects of several hormones. This ability allows for previously unforeseen situations to be dealt with and for conflicting demands upon the robot to be resolved. This is advantageous in such an environment where computational power is severely limited. It is envisaged that the Artificial Endocrine System will act as a closed feedback loop in which the release of hormones triggers actions which in turn affect the state of the robot and as these changes are sensed the glands will reduce their hormone output. Should the hormones fail to produce the desired result then their concentration may be increased until the desired changes are observed.

There are some potential caveats with such emergent behaviour (that are not unique to this approach) in that undesirable behaviours may also emerge and the end user will be unlikely to predict these behaviours or be able to intervene given the geographical isolation of the robot and the non-realtime nature of the communications systems. It may therefore be desirable to introduce some kind of safeguard system to prevent exceptionally poor decisions resulting from a neuro endocrine system or to record and score decisions which are made and prevent low scoring decisions from reoccurring.

It is also proposed to introduce redundancy into the robot in the form of redundant actuators, sensors and computers. This will aid the goal of long term autonomy even in the event of component failure. A sailing robot also presents an interesting case to study the use of secondary control mechanisms, as movement of the sails' affects the boat's heading a sail can be used as a secondary steering mechanism. Such secondary mechanisms can serve two purposes, the first is to act in cooperation with the primary system in order to improve its efficiency and the second to act as a backup in the event of a primary system failing.

6. Conclusion

This work has demonstrated that it is feasible to construct a sailing robot capable of following a simple predetermined course using off the shelf parts. It has also demonstrated the difficulties associated with producing suitably robust hardware and software required for such a robot. Further development is required to demonstrate the feasibility of a sailing robot for long term use in the open sea, it is likely that a larger hull will be required for this in order to accommodate a payload of instruments which are of use to oceanographers and environmental scientists. Future software development work will focus on neuro-endocrine controllers intended to improve survivability and the ability to remain at sea for long periods. Future hardware development will focus on the construction of a physically larger and more robust prototype. One area of hardware development which particularly requires focus is that of sail reefing (adjust the size of the sail), solving this issue will dramatically reduce the strains of sailing in high winds. It is hoped that once these issues are solved a mission returning scientifically useful data from the ocean can be achieved.

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