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Neal, Mark

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Technical communication:

A hardware proof of concept of a sailing robot for ocean observation

Dr. Mark Neal,
Intelligent Systems Laboratory,
Department of Computer Science,
University of Wales, Aberystwyth,
Ceredigion, SY23 3AF, U.K.,
mjn@aber.ac.uk

***Abstract*— A design for a sailing robot capable of holding station in a variety of wind and sea conditions is described. Results from experiments with an autonomously controlled small-scale prototype on a lake are also presented. The likely effects and problems of scale-up are examined, as are the cost considerations. Potential applications for a larger version of the robot are discussed and the requirements for communication and long term autonomy are considered in the light of the results obtained with the prototype.**

The potential for low-cost, flexible, in-situ ocean observation is examined and likely capabilities of a system based on this type of robot are considered.

***Index Terms*— Mobile robots, marine vehicle propulsion, sailing, marine vehicle control, ocean observation**

I. INTRODUCTION

THE development and deployment of autonomous robots for a number of applications has been successfully completed, most notably for planetary exploration. Whilst the use of unmanned (both tethered and drifting) buoys for ocean observation is well established, the use of unmanned systems capable of long term purposeful navigation is still in its infancy. A large number of autonomous underwater vehicles (AUVs) have been developed[1], [2], [3], but little experimentation with surface vehicles has been undertaken[4], [5], [6], [7], [8]. Electrically or combustion engine propelled surface and underwater vessels must suffer severe limitations on endurance or be engineered on a very large scale in which case the need for, and advantage of, unmanned operation disappears. Sail propelled vessels thus prove an attractive prospect for investigation.

The author considered a number of platforms as potential candidates for conversion to autonomous operation. A range of model yachts, sailing dinghies and very small cruising yachts were examined, but a number of difficulties arose with each. Model yachts are built with particular racing classes and conditions in mind and for these reasons have shallow keels and are not intended to be used in rough water: simplification or replacement of the mast and rig and drastic modification and strengthening of the hull for a deeper keel would be required. Sailing dinghies will also require drastic modification to make them self-righting as well as requiring a modified rig to allow reliable automatic control. The best candidate hull is a small cruising yacht which is already self-righting and with a covered deck. The rig for such a vessel still provides a number of problems however and would require a large amount of custom engineering of winches and/or other sail control mechanisms. The resultant vessel would be large, heavy and expensive and would still rely on fabric sails that are relatively fragile even when carefully tended by crew.

For these reasons the author has built from scratch and tested a small-scale vessel to prove the concept of an autonomous sail propelled robot for ocean observation. The prototype measures 1.5m in length and carries a solid, rotatable “wing-sail” 1.3m in length. This prototype is intended to prove the concept and potential usefulness of a slightly larger design which would be better suited to long term autonomous operation in the open ocean. The final design is expected to have an overall length of 3m and displacement of 100kg of which around 10kg will be available as scientific payload. This size is a reasonable compromise between sea-going ability which generally improves with size and ease of launch and recovery. The final design is intended to be launched from a small craft at around 10 miles from shore. The robot will then sail out to its destination location where it will hold station for as long as possible (a timescale of a few months is initially envisaged), after which it will return to the coast and be picked up once more by a small craft for servicing, repairs, anti-fouling and relaunch.

II. THE SMALL-SCALE PROTOTYPE

The small-scale prototype is intended as a proof of concept for a sail propelled robot with a number of key characteristics:

1) Station-holding capabilities under a wide range of wind and sea states
2) Useful payload capability
3) Low power consumption
4) Capability for long term autonomous operation

Points 1) and 2) both imply a larger rather than a smaller robot, however the nature of the resources available for construction and testing of the robot dictated some very real restrictions on the scale of robot to be built. It was essential that the initial

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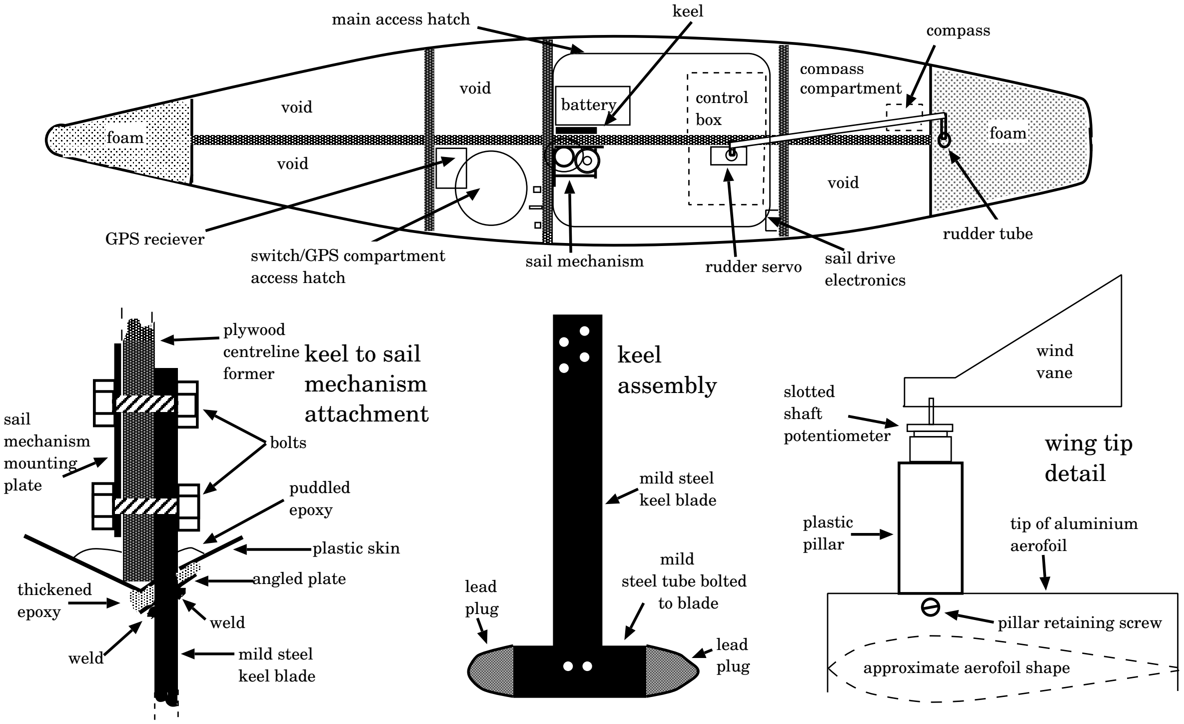


Fig. 1. Details of general construction (not to scale)

prototype could be transported in a large estate car to allow access to the inland lake test-site, and that it could be handled. After consideration of a number of approaches to the design and construction of the hull a radio-control yacht hull form was chosen as a basis. This was a 1.52m (60in) design [9] (which just fits into a large estate car) with a displacement of 12kg (25lb). The hull is of hard-chine construction which proved relatively cheap, easy and sufficiently efficient for the purpose of testing the concept. From the outset a solid wing-sail was selected for ease of control, construction, efficiency and robustness. This also proved to be a reasonable selection in as much as it proved adequate for testing the concept.

A. Design and construction

After selection of the hull form a careful redesign was undertaken in order to improve stability in strong breezes and relatively large waves. The simplest way to achieve this was to dramatically increase the keel depth which was restricted due to class rules in the model design. The initial draft was restricted to 23cm, and was increased to 55cm subsequent to the modifications. In order to maximize the effect of the modification, as much as possible of the ballast (3.5kg) was attached to the bottom of the steel keel fin in the form of a lead bulb.The keel was placed so as to ensure that the overall centre of lateral resistance (CLR) of the hull did not move after the redesign. Likewise, the ballast mass was arranged so as to maintain the fore-and-aft position of the centre of gravity.

1) Hull and keel construction: The hull was built around a central plywood “keel” and three plywood bulkheads. These were all cut by band-saw from 12mm ply and glued and screwed together to provide a stiff structure upon which to form the external skin of the hull. All of these components were lightened where possible by cutting out excess material. The hull skin was cut in 3 sheets per side from 4mm ABS which were screwed and glued in place. In addition, the fore-most and aftermost bulkheads were cut from 4mm ABS. The plastic hull skin stops 15cm short of the bow and 25cm short of the stern in order to allow the use of polyurethane foam in these damage-prone regions. Subsequent to hull construction the foam was sprayed into place and then carved to shape and hardened with a thin epoxy coating. After the hull was glued and filled where necessary a 1mm ABS transparent sheet was fixed as decking. This extended to the full length of the hull and had three apertures cut in it to allow access to: the main compartment aft of the mast which houses the battery, actuators, computer and other electronic components; a small charging and switch panel in the forward, port side compartment; and a small fluxgate compass compartment at the stern. At this stage the rudder was constructed and mounted to the stern plastic bulkhead. The rudder blade was carved from 12mm ply and attached with a bolt and epoxy to a length of 6mm extruded fibreglass rod which protrudes through the deck and is fitted with a control horn above deck level.

The keel blade was constructed from a 55cm length of 50x5mm mild steel. The bottom 45cm were profiled to an approximately symmetric aerofoil using a bench grinder and files. A 80x25mm plate was cut to fit around the keel blade at the top of the profiled section and welded into place at a suitable angle to match the shape of the bottom chine of the hull. The keel was placed 6mm off-centre in order to allow it

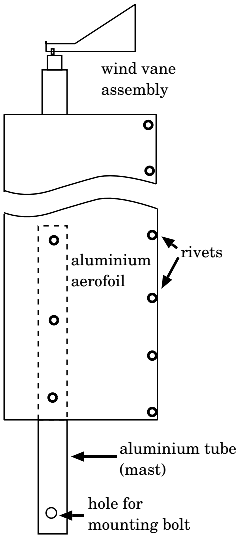


Fig. 2. Overall wing-sail construction (not to scale)

to be bolted to one side of the centreline former in the hull and the plate welded to the keel blade was used to provide a sound and watertight joint where the keel blade passes through the hull skin. This was sealed with thickened epoxy externally and a puddle of unthickened epoxy was formed inside the hull around the keel blade. The keel blade was bolted to the centreline former using 4x5mm bolts, which also pass through the wing-sail actuation mechanism on the opposite side of the former. This provides a very strong and direct mechanical connection between the hull, keel and wing-sail. Figure 1 shows a number of sketches of key construction features.

2) Sail mechanism construction: The wing-sail is formed from 1mm aluminium sheet wrapped into an aerofoil section around a short length of 32mm aluminium tube which is used as a wing root at the bottom of the wing-sail. Aluminium rivets are used to hold the trailing edge of the aerofoil together and to attach the aerofoil to the wing root (see figure 2). The tube at the wing root is attached to the actuation mechanism which is bolted to the centreline hull former, the centre bulkhead and the keel with a total of 8x5mm bolts. The actuation mechanism uses a 12v AirMax motor and gearbox assembly with a rotational speed of 60 rpm mounted on a further reduction gear to yield a final rotational speed of about 2rpm. This mechanism also incorporates a potentiometer for position feedback and allows sufficiently precise and repeatable control to facilitate a wide variety of points of sail to be achieved from “hard on the wind” to a dead run. Mounted at the top of the aerofoil is a short plastic pillar which carries a second potentiometer fitted with a wind vane. This is used to determine the wind direction with respect to the aerofoil in order to allow adjustment of the wing-sail angle and/or the course to be sailed. Figure 3 shows details of the wing-sail control mechanism.

3) Control hardware components: The main controller which drives the wing-sail actuator and rudder servo (a standard pulse-width-modulated servo) consists of a Stamp[10] single board computer (SBC) and a slave PIC[11] microcontroller board. This is an easily obtainable off-the-shelf and low-cost item which provides sufficient performance to test the concept. The Stamp is programmed directly from an IBM PC compatible computer serial port using standard software and a simple BASIC style language. The Stamp runs a program (described in more detail below) which drives the wing-sail actuator hardware and the rudder servo to the desired positions for the current point of sail. It also reads the current heading from the flux gate compass, the wind direction from the wind indicator potentiometer and the wing-sail position from the wing-sail position potentiometer. The potentiometers are read with a simple one-line analogue to digital conversion technique using capacitor discharge time to measure the potentiometer position. The flux gate compass provides a pulse width modulated output which indicates the heading. Thus in total there are only 5 low-level hardware devices under consideration. All of these components communicate via serial interfaces which are mediated by the Stamp SBC. All electrical power is provided by a 12V 4.2Ah sealed lead-acid battery. Various voltage regulators and fuse systems protect the devices powered from the battery. There is no electrical energy generation facility fitted to the small-scale prototype, although the addition of a photovoltaic array to the surface of the aerofoil is planned. At present the battery fitted is capable

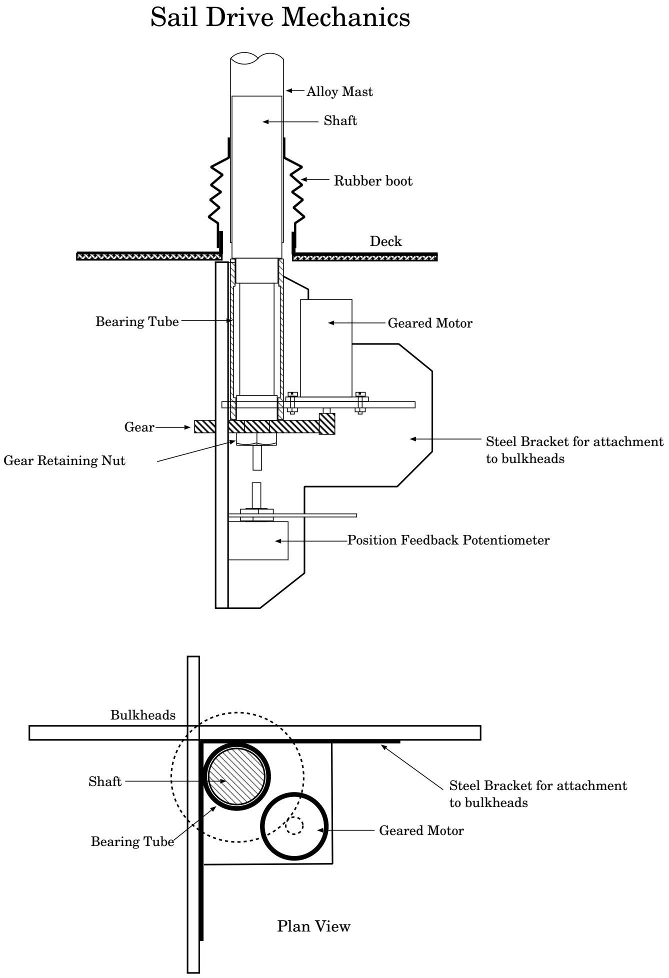


Fig. 3. Sail rotation mechanism (not to scale)

Fig. 4. Robot sailing on lake during experiments

TABLE I

ENERGY BUDGET STATISTICS

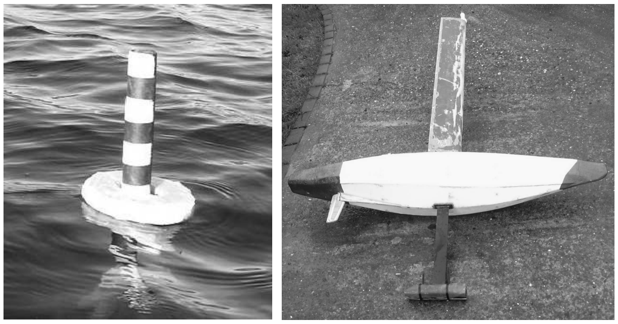
	Current drawn at battery terminals			
Component	Standby	Average	Harsh	Maximum
Stamp SBC + PIC	10mA	35mA	65mA	150mA
Rudder servo	10mA	50mA	150mA	500mA
Sail mechanism	$<$ 1mA	10mA	50mA	500mA
Compass	20mA	20mA	20mA	20mA
Total	40mA	115mA	285mA	1170mA
Battery life (hours)	84	36	15	3

of powering the robot for periods far longer than any of the experiments so far undertaken: a realistic minimum battery life of 18 hours (in conditions requiring frequent changes in rudder position), and a battery life of around 36 hours in less difficult conditions is projected. Energy budget statistics and contributions are shown in table I.

B. Control

The control program implemented for the experiments was not intended to be "intelligent" or optimal in any sense, but to demonstrate that the robot was controllable and sufficiently efficient when sailing to be a useful platform. The development of more complex, ambitious and "intelligent" programs in the future is one of the main motivations for the development of the robot.

The windward sailing experiments carried out on the lake use a simple control loop which uses incremental changes to the rudder position (in effect a pure integral controller) to attempt to maintain a constant wind direction reading from the wind vane mounted at the masthead. The wing-sail was kept at fixed angles on each sailing leg during these experiments. This control algorithm is not good at coping with variable wind directions and speeds such as those encountered in experiments on the lake. This led to accidental tacking and gybing in these difficult conditions. It is worth noting however that even a skilled dinghy sailor experienced similar problems when sailing on the same lake in similar conditions. The



(a) Simple wave height monitor in calm conditions. The white disc is polystyrene and is free to travel up and down the scale pole. Each band on the scale is 2.5cm wide.

(b) The complete robot as tested. The extreme nature of the keel and small skeg can clearly be seen. Overall length is 1.5m and displacement is 12kg.

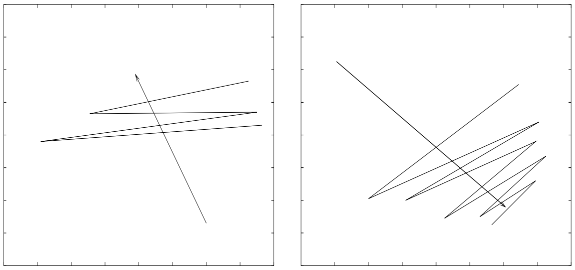
Fig. 5. Experimental equipment.

TABLE II
RESULTS SUMMARY FOR LAKE EXPERIMENTS

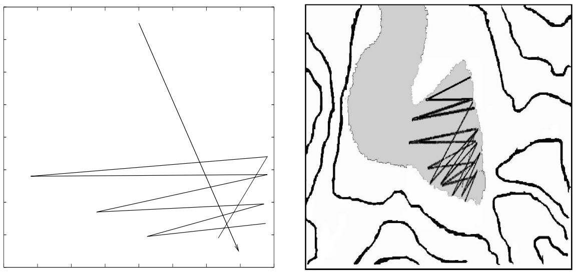
	Expt. 1		Expt. 2		Expt. 3	
Tack	Port	Stbd	Port	Stbd	Port	Stbd
C.M.G. relative to wind	95° ‡ ‡ 101°‡	65° ‡ ‡‡ 71°‡	68° 70° 72° ‡ ‡† 83° 74°	100° 97° 89°‡ 88°	81°† 84°‡ 85° ‡ ‡	85° 79° 75°
Means	98°	68°	73.4°	93.5°	83.3°	79.7°
Expt.	83°		83.4°		81.5°	
Overall	82.6°					

TABLE III
WEATHER SUMMARY FOR LAKE EXPERIMENTS

Expt. 1			Expt. 2			Expt. 3		
Wind(mph)		Waves	Wind(mph)		Waves	Wind(mph)		Waves
5	20	5cm	8	8	2.5cm	7	20	7.5cm



(a) Experiment 1 (b) Experiment 2



(c) Experiment 3 (d) Surrounding terrain

Fig. 6. Tracks followed by the robot in three experiments on the lake. Arrows show wind directions. (d) shows contours surrounding lake and relationship to experiment areas. The North Western arm of the lake is too shallow for the robot.

wind is very gusty and varies dramatically in direction when blowing from the South (experiment 1). It is worth noting that for other wind directions the problems did not exhibit themselves as significantly.

A proportional-integral controller is currently undergoing testing and development and is showing some promise in sailing more efficiently to windward.

C. Performance

Whilst the sailing performance of the robot is not as good as had been expected (teleoperation of the same robot in similar conditions achieves significantly better windward performance), it is clear from the results that the robot is capable of sailing to windward fairly effectively. It should also be borne in mind that very little effort has yet gone into the development of software and control algorithms. It is likely that the proportional-integral controller currently under development will achieve much better rates of progress to windward. Short, informal experiments suggest that courses made good to windward at angles of around 70° are to be expected. The design changes made to the keel have increased the righting moments dramatically, and even in wind strengths of up to 35mph the robot retains steering control and whilst heeling dramatically, rarely exceeds 45° and rapidly rights itself in the event of a complete “knock-down”. Clearly the ability to adjust sail area dependent on wind strength would assist dramatically in the ability to deal with widely varying conditions, but it seems likely that even a simple rigid wing design such as that presented here may prove sufficient for some station holding tasks.

D. Results

Results from the lake trials are summarized in table II[1]. Experiment 1 was shortened due to the wind dying away to less than 1mph after the 4th leg. Wind conditions during experiment 1 were extremely variable due to the nature of the surrounding terrain. Shifts in direction of more than 90° occurred and in general the wind was very light. Weather conditions during each experiment are summarized in table III. The tracks achieved by the robot in the lake trials are shown in figure 6. It is clear from the track plots that in all the experiments the robot achieved a steady but slightly disappointing rate of progress to windward. It is also clear that the course made good to windward on each leg varied significantly both within and between experiments. This seems to be due to the unsteady nature of the wind on the lake but may also be due to the asymmetric keel and sail positions. Observation showed that the starboard tack was less prone to accidental tacking and gybing than the port tack. The gross disparities in averages for port and starboard tack are possibly also caused by the difficulty of measuring the wind direction on the lake: the eddies and variations in wind direction both around the edges of the lake and in its centre make this almost impossible to achieve.

III. FULL-SCALE DESIGN CONSIDERATIONS

It is the intention of the author to construct a similar but larger robot able to sail effectively in a much wider range of weather conditions and to perform environment monitoring tasks requiring significant payloads and very extended periods of autonomous operation: continuous operation for 6 months

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[1] Dagger symbols represent accidental tacks/gybes: † represents one and ‡ represents two.

would be a suitable goal. The final robot is intended both as a scientific monitoring platform and as an exploration of the limits of autonomous sailing robot operation in an open ocean environment.

The size of the robot is determined by a number of factors including ease of handling from small craft, cost and sailing performance. A reasonable compromise can be made at around 3m length overall and a displacement of around 100kg. These figures scale directly from the prototype (1.5m length and 12kg displacement) by simply cubing the length scalar (in this case 2) and multiplying the original displacement. A 3m robot should be able to cope with dramatically more wind and wave action than the prototype, and thus be far more useful in an open ocean scenario.

A. Design and construction

Clearly the hull construction of the robot is a crucial part of the overall design, and a number of lessons have been learnt from experimentation with the prototype:

1) Accidental impacts happen
2) The number of openings in the hull needs to be kept to a minimum
3) Simple and easily testable seals for hull openings reduces the opportunity for water ingress
4) Magnetically activated switches can be activated without hull openings
5) Directional stability reduces steering actuator power consumption

These factors indicate a number of potential construction materials and methods. Impact damage is well resisted by metal structures which are also well understood and relatively easy and cheap to build. The obvious low cost and robust option is that of relatively thin steel which with an overall length of 3m and displacement of 100kg should be possible. A simple scaling of the current hull design would require approximately 2.5m^2 of hull and deck plating and less than $0.5m^2$ of internal structure. Assuming that the hull plating is 1mm thick and the internal structure is 2mm thick this gives a total approximate hull weight of $8\times2.5+16\times0.5=28$kg. The use of a suitable grade of stainless steel would reduce problems with corrosion and make the use of a flux gate compass simpler. The number of openings in the hull cannot realistically be reduced to less than three: rudder actuation mechanism, sail actuation mechanism and a cable gland for external sensors, antennae and photovoltaic arrays. The long period between services for the robot means that securely bolted or even welded covers can be used for access to components like batteries and control equipment. A simple flexible rubber boot can be used to seal the rudder actuator: the relatively short compression and extension motion of an actuation rod can easily be absorbed in a “bellows” type boot. A secondary sliding shaft seal will provide a secondary barrier to the ingress of sea water should the boot become damaged. The seal around the base of the wing-sail is rather more problematic as at least 180° of movement must be possible. In the prototype a number of methods were tested for this seal including polythene and rubber boots. These loose tubular boots formed sharp kinks when rotated and are severely stressed and prone to chafe at a number of points. Whilst such a boot might provide outer protection, it seems that the use of rubber lip seals or some form of “stuffing box” arrangement would be a good second level of defence. An arrangement with an outer rubber boot and at least one rubber lip seal seems appropriate. A dual lip seal system for this seal has been successfully tested on the small scale prototype, but requires refinement in both engineering and lubrication in order to be sufficiently reliable. A facility for pressurization (to a few psi) of a completely assembled and sealed hull through a removable and pluggable air valve would provide a simple and reliable testing method for such seals.

A simple reed switch was used in the prototype to allow the microcontroller to be reset without opening any hatches: the use of magnetically operated switches (through the hull) means that the robot can be completely sealed in a well controlled environment and “activated” only when launched. The hull design used for the prototype was extremely manouverable, and thus required frequent changes of rudder position to maintain a steady course. The use of a more conservative keel profile and/or a larger skeg would increase directional stability and reduce power consumption by the rudder actuator. Clearly any design changes made to the hull would need to consider the positions of the centre of lateral resistance, centre of gravity and centre of effort of the wing-sail.

Possibly the most problematic decision to be made is whether or not to provide the ability to “reef” the sail. The ability to increase or reduce the sail area by some significant percentage would extend the range of conditions in which the robot could sail effectively, and thus its ability to sail to, and maintain positions effectively. A number of mechanisms have been considered, and it seems likely that either a relatively simple arrangement of flat plates that stow inside the wing sail and can be rotated out through a slot in the trailing edge, or a telescopic aerofoil will be employed. These mechanisms would allow adjustment of the sail area in the range of 50-100% which is expected to improve performance in strong winds without affecting light-wind performance adversely. These mechanisms are likely to be chosen over more complex systems based on aircraft “flap” styles for ease of construction, reliability and low cost. It is intended to use off-the-shelf actuators where possible.

B. Control, communications and energy budget

Control of the larger robot should prove very similar to the small scale prototype, thus a similar level of low-level processing is likely to be used. PIC based computers are very flexible and low-cost and are more than adequate for these purposes. The full size robot will however have a number of other computational requirements. These will include the control of the reefing system which will also involve the monitoring of an additional wind strength monitor, as well as much higher level mission control tasks such as data transmission and reception and route planning. It is thus envisaged that a more capable computing platform will be installed in the robot in addition to the low-level PIC based

TABLE IV
PROJECTED ENERGY BUDGET STATISTICS

	Current drawn at battery terminals			
Component	Standby	Average	Harsh	Maximum
Microcontroller system	50mA	100mA	150mA	500mA
Rudder servo	10mA	100mA	150mA	1000mA
Sail mechanism	< 1mA	10mA	150mA	1000mA
Compass	20mA	20mA	20mA	20mA
Communications	< 1mA	50mA	50mA	50mA
Total	80mA	280mA	520mA	2570mA

systems. This is expected to be based around a low-power ARM-based microcontroller. This should provide sufficient processor power and memory to enable effective use of the robot's resources and task performance. There will also be a requirement for long range communication of data, and the inclusion of satellite communication equipment seems to be the best choice with respect to power consumption, bandwidth, coverage and reliability. The impact of these additional systems on power consumption is significant, and overall projected energy budgets are summarized in table IV. The use of photovoltaic arrays on the sail surface should permit a total of around 2m^2 of collecting area, only half of which will be exposed to any available sunlight (half will be on each side of the sail). 1m^2 of photovoltaic cells generates a peak current of around 6A at 14V (sufficient for charging lead-acid batteries). Clearly this is only under optimal conditions, so by assuming an average of 500mA continuous we reach a realistic estimate of expected photovoltaic performance. This should allow for night-time as well as low angle of incidence conditions due to heeling and cloud cover. Initial calculations indicate that 500mA should be sufficient for a balanced energy budget over long periods of time when combined with a large battery pack to act as a reserve for long periods of low intensity light.

C. Projected production cost and performance

Initial estimates made in conjunction with an established bespoke robot manufacturer[12] indicate that the detailed design, jig building and construction of an initial full scale prototype will cost in the region of £40,000. This is assuming that large numbers of components will be used off-the-shelf, and that there are no major design changes from the small scale prototype. Assuming a welded stainless steel hull construction table V presents an estimated breakdown of subsequent low volume production cost per unit.

TABLE V
PROJECTED COST BREAKDOWN

Component	Cost
Hull assembly	£4,000
Sail assembly	£4,000
Sail actuators	£3,000
Rudder actuator	£2,000
Microcontroller system	£2,000
Batteries	£1,000
Communications	£2,000
Sensors	£2,000
Scientific payload	variable
Total	£20,000

IV. A POTENTIAL OBSERVATION SYSTEM

The need for in-situ monitoring at sea does not seem to be in dispute amongst oceanographers [13] and it is interesting to speculate what might be achieved if a small fleet of such robots was available for continuous deployment and rotation. If reliability of operation for a period of 8 weeks is achievable then this opens up a number of possibilities for simple station holding observation tasks. If the robots are capable of achieving speeds of 2 knots on average, then this means that over an eight week period they will be capable of covering in excess of 2500 miles. It is realistic to expect that for a sailing vessel approximately half of that distance will actually be course made good to an arbitrary position. Nonetheless, if a location is selected that is 250 miles offshore then the robot should be able to spend around 30 days on station before requiring relief by another robot. The use of 2 such robots in rotation would allow sufficient time (14 days) between launch and recovery for servicing the robots. This regime would require a launch/recovery approximately every 21 days which could be undertaken using a small-craft such as a rigid inflatable boat or inshore fishing vessel. Clearly larger numbers of robots could extend the range offshore that could be monitored, but the singlemost important factor governing both cost and flexibility of monitoring locations is the time for which the robot is able to operate autonomously. Increasing the period between services to 25 weeks would enable the monitoring of positions up to 750 miles offshore using only two robots. It is the author's belief that autonomy for such periods is achievable with this type of robot, and it is with this goal in mind that the development of the robot is being undertaken.

V. CONCLUSION

The work presented here proves that production and control of autonomous sailing robots is possible, and that reasonable performance can be obtained from low-complexity and low-cost components. The possibilities for long-term autonomous operation have been discussed and presented as a real possibility for the near future. The construction of a small fleet of autonomous sailing robots would add an extra string to the bow of oceanographers and climate scientists for obtaining in-situ measurements and samples at sea. Whilst the ocean surface is clearly an extremely hostile environment for engineered systems the initial indications from this work are promising mainly due to the mechanically simple nature of the robot.

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Mark Neal is a lecturer in Computer Science at the University of Wales, Aberystwyth where he works in the Intelligent Robotics Research Group. He has extensive experience in both the development of mobile robots and ocean-going sailing.