Control System for International Moth on Hydrofoils
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Abstract

Moths are meant to go fast, the fastest 11' dingy in the world that is!

The international moth is a single man sailing dingy at the fore front of development. There are few restrictions on the design and it is the only class of sailing dingy that has not band hydrofoils. Currently there is only development being carried out in Australia although a UK boat builder is about to start making foils.

Currently mechanical control systems are used to automatically adjust the 'fly' height of the boat, however these systems are difficult to implement, requiring long setup times and sensor 'wands' dragging in the water. I propose an electronic control system that will control the fly height of the boat. The system needs to be robust and ensure the safety of the sailor.

Contents

1.0 Introduction

During the past ten years the design of the moth has stagnated with designs of around 30cm wide and pin tail sterns. The three major designs of this period are the Skippy, hungry tiger and Axeman 7 with all three having similar dimensions and performs roughly the same. Before these designs moths were wider, spawning several new classes during their development. The most notable are the Europe, being about 1.3m wide and now an Olympic class for woman and the RS300, a mass produced one design.

During the eighties the Magnam series of designs ruled the roost, being about 50cm wide at the eighth generation. The moth class then went under a big change with the introduction of that Axeman series of moths from Bloodaxe boats. The first, the Axeman 1 was the first 'narrow' moth with its angular lines and a water line width of 35cm. This design failed to produce a world or national title but heavily influenced the next Mangum design, the Magnum 9. This design was much deeper than its processors and featured a narrow slab sided box with a width of 35.6cm. This design won the worlds in 1990. The shape of the hull was refined by adding curves and a narrower transom increasing performance but there have been no major design changes since. See appendix 1 for complete list of design.

Hydrofoils are revolutionising the moth class, the performance increase is perhaps the biggest increase in performance of sailing boats since the 18' skiff class was revolutionised by Julian Bethwaite in the 1990's. To give an idea of the gains, the handicap of the moth is expected to drop from 1000 to around 850 with the addition of hydrofoils. To put this in context, in a 100 minute race the difference between a moth with and without hydrofoils will about 8.5 minutes, approximately a 20% increase in speed! A video entitled john_and_glen_2.wmp which is on the enclosed CD shows this speed potential very well. Two moths are together, a foiler and non foiler. After a nose dive the non foiler is slightly in front, suddenly the foiler lifts out the water and shoots past the other boat.

I started by carrying out research into past and current hydrofoil design, I considered the design merits of each, and how they applied to this project. I also did research into foil construction, especially carbon laminates, control theory and controller design.

In this report I will discuses the various design issues associated with applying hydrofoils to a moth, develop a mathematical model, design a controller and finally implement this in hardware.

2.0 Literature – Existing Designs

A few moth designs have used hydrofoils successfully. I will discus the relevance of each to modern hydrofoil design and also consider the design merits of each.

2.1 Wing mounted foils

One of the first moths with hydrofoils was designed and built by Brent Burville. Pictured below, it has wing mounted surface piercing foils. There have been a few moths with this and similar configurations and this particular moth was used at the 2000 worlds.

The boat was supported by two foils attached at the front of the wings and a very deep rudder with a large T foil at its base. The front foils were generous in size and were angled inwards by about 45 degrees, known as Bruce foils. They were capable of lifting the boat out of the water in under 10 knots of wind. When going well in ideal conditions the speed Brett achieved was truly awesome - possibly comparable to a 49er!

The main issue with the foils was control. Sitting too far back in the boat caused the front foils to porpoise upwards and then stall, producing a usually catastrophic nose-dive. Heeling

the boat excessively to windward would cause the leeward foil to come out of the water, the windward foil would then slide in on itself producing a sudden windward lurch and nose-dive. This behaviour was particularly a problem when sailing side on to waves (i.e. on most of the legs of an M course!) when the leeward foil went into a trough. Upwind the foils were quite straightforward to sail, even in rough conditions. Quite unexpectedly it was found that the boat could be tacked *faster* on foils than without. It was not unusual for Brett to get to the top mark well clear of the fleet, but to have dropped many places by the time he reached the bottom mark.

There is no control system on this craft; the height (and roll to a certain extent) is controlled automatically. As the boat lift out the water there is less foil in the water and so less lift is produced. The boat eventually arrives at equilibrium.

However recent interpretations of the class rules have deemed this configuration as illegal due to breaking the multi hull rule (see appendix for full class rules) so development has ceased on this configuration.

Early hydrofoils mounted from the wings.

2.2 Dagger board and Rudder mounted foils

Due to the class rules changing and problems with waves with wing mounted foils, there was a move to attach the hydrofoils to the rudder and centre board alone. The first person to do this was Ian Ward in mid September, 2002, followed shortly by John Illett.

A small trim tab was located on the trailing edge of the foils, much like an aeroplane. A wand type sensor then drags in the water to control the height (This is studied in more depth later). Below is a picture showing this configuration. Note the wand on the port bow.

This design won the recent Australian nation championship with straight firsts, and also won some races at the last world championship. It has proved faster than a conventional moth around a course, and is less susceptible to waves than previous designs.

The control for this design consists of movable flaps on the two foils. The flap on the dagger board is controlled automatically by the wand skimming the water surface, while the rudder flap is adjusted by the sailor by twisting the tiller extension. In practice, once the rear flap has been set for a particular condition it is left in a set position. I think it will have to be adjusted for different wind strengths and maybe different legs of the course since the lift that the rear foil produces will change according to the velocity of the boat.

Garth Illett foiling with the hydrofoils attached to the dagger board and rudder only.

2.3 Existing sensors

The lift that the foils produce will change depending upon the velocity of the boat. Since the down force generated by the boat is not dependent upon boat speed, the amount of lift generated needs to be regulated. Ideally a constant fly height is desirable, but there's a band where it is acceptable for the boat to be in. The hull needs to be out the water, but the foils still submerged; this means the height needs to be controlled.
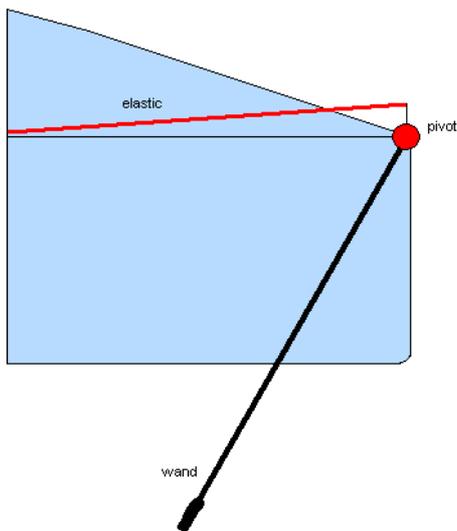
To sense the height the prowler uses a wand type arrangement. A stick is attached to a pivot and is held down with elastic. When it makes contact with water it deflected upwards. A control cable connects the wand directly to the flap on the hydrofoil flap. The flat position is proportional to the fly height.

Bow arrangement of Fastacraft moth. Note the use of a power boat throttle cable for the control cable.

Prowler design of moth with foils mounted on the dagger board and rudder out the water.

The wand is clearly visible, tied up at the bow.

This is the only sensor system currently implemented on moths.

2.4 Foil design

There are several different ways of manufacturing foils for dinghies. The oldest way is to start of with a plank of timber. This is then cut into strips and the strips reversed in direction. These strips are then glued back together. This process stops the plank from warping. Next the foil is shaped with normal wood working tools to the desired section. To finish the foil it is painted and sanded smooth. To increase the stiffness of the foil carbon fibre can be added to the outside. This is very effective in increasing the performance of the foil for little cost.

The problem with wood cores is they are heavy; foam can replace the wood if more carbon is added to the outside. This is how many high performance foils are manufactured. To improve accuracy the core can be computer cut, producing very accurate sections. The only problem with this method is that when the carbon is applied to the outside differences in the thinness of the lay-up can distort the section. Normally dinghy foils are around 15mm – 20mm thick so a deviation of 0.5mm is no problem. The hydrofoils for the moth have a chord of 120mm and a thickness of 12%. This mans a thickness of 14.4mm, less than normal foils. To compound the thickness problem the section is cambered so the trailing edge is very thin for a large portion of the foil. A small error in the skin thickness will have a large affect on performance.

A different way to make foils is to mould them. Laser, injection mould plastic around a steel frame to produce their mass produced foils, while the finish and section is good they are very heavy and not producible on a small scale. Strength wise they are poor and prone to large chunks breaking off. The section that is used is also thick, this allows a significant about of steel to be used to produce the required strength. The production technique used by John Illett is also a moulding process, but he moulds the foils in two halves in female moulds using a composite lay-up of carbon/epoxy resulting in a hollow foil. I will endeavour to use a similar process.

The foil section used is critical for good performance. NACA are one of the best know bodies for designing aerofoil sections, with their 00xx series of sections being the most

widely used series on dingy foils. This section features good stall characters and is able to operate at relatively high angles of attack. However there are better sections for low angles of attack that feature a drag bucket such as the 64 xxx series. The drag bucket is a region where the foils have very low drag and can been seen on the data sheets for the 64 412 aerofoil. The down side of these sections is they will stall earlier and once you are operating out of the drag bucket the performance is worse that 00xx section. This sort of section is used on foils that only operate at low angles, say the dagger board and hydrofoils, while a 00xx section would be more suitable for the rudder since this has to operate at higher angles of attack. The thickness is expressed as a percentage of the cord, with 12% being a good compromise between low drag and high lift. Sections with 9% thickness were also considered, the advantage for using a thinner section is lower drag. However there is less lift available and having a thinner wing imposes structural problems. For this reason I opted for a thinness of 12%.

2.5 Video study

I have enclosed the videos that I have studied on the enclosed CD. Studying these was important in understanding the dynamics. First I looked at the stability of the boat; in a few videos the boat tended to oscillate a little, I assume this was before the control system was perfected, but generally it was fairly stable. The steady state error is generally large with the boat tending to be too high, and in danger of the foils cavitating, or too low with the hull dragging in the water. I think this issue has now been resolved by careful adjustment of the linkages, but ware and tare in the linkages is likely to disturb the system, probably resulting in the need to constantly adjust them.
External disturbances, such as waves cause problems with this system. The boat will have low pass characters so the boat will tend to try and follow waves. I think a particular sizes of wave will cause the most problems; ones that are not big enough, i.e. too high in frequency, to follow, but are of a sufficiently low frequency for the dynamics of the boat not to filter out. In general I think that stability and performance could be enhanced with a suitable filter and control system.

3.0 System Design

The configuration of the foils is pretty much set as to T foils by the class rules. As regards the dimensions of the foils themselves I will initially run simulations with foils of the same dimensions as the prowler has, then experiment with different sizes to see if a performance increase can be found.

The controller will be implemented in software on a microcontroller, so I will need to devise a way of measuring the fly height of the boat so that calculations can performed on it.
The next section looks at the controller design in more detail.

4.0 Nomenclature

$H(s)$	transfer function of generic controller
K_P	proportional gain
K_D	differential gain
K_I	integral gain

ρ	Density of water
v	velocity of foil thought liquid
AR	aspect ratio of foil
S	complex variable
H	fly height

S	area of foil
S_{DH}	area of hydrofoil attached to dagger board
S_{RH}	area of hydrofoil attached to rudder
S_D	area of dagger board
S_R	area of rudder

L	lift generated by a foil
L_{DH}	lift generated from hydrofoil attached to dagger board
L_{RH}	lift generated form hydrofoil attached to rudder

D_p	parasitic drag from foil
D_{total}	total drag of foil
D_i	induced drag from foil

D_D	drag from dagger board
D_R	drag from rudder
D_{RH}	drag from rudder hydrofoil
D_{DH}	drag from dagger board hydrofoil
D_T	total drag from foils

α	general angle of attack of foil
α_H	angle of attack of hydrofoil
α_{RH}	angle of attack of hydrofoil attached to rudder
α_{DH}	angle of attack of hydrofoil attached to dagger board

C_L	general lift coefficient of foil
C_{LH}	lift coefficient of NACA 64 412 section used on hydrofoils
C_{LD}	lift coefficient of NACA 64 012 section used on dagger board
C_{LR}	lift coefficient of NACA 0012 section used on rudder

C_D	general form drag coefficient of foil
C_{DH}	general form drag coefficient of hydrofoil
C_{DDH}	form drag coefficient of foil used on hydrofoil attached to dagger board
C_{DRH}	form drag coefficient of foil used on hydrofoil attached to rudder
C_{DD}	form drag coefficient of foil used on dagger board
C_{DR}	form drag coefficient of foil used on rudder

a_x	forwards acceleration
a_y	vertical acceleration
β	sheeting angle
M_{total}	total mass of craft, i.e. mass of sailor plus mass of boat
F_{sail}	force from sail

5.0 PID controller

The PID algorithm is the most popular controller structure used in industry and it has been successfully used for over 50 years. It is a robust, easily understood algorithm that can provide excellent control performance in many different systems. PID algorithm consists of three basic modes, the Proportional mode, the Integral and the Derivative modes.

These 3 terms affect the plant in different ways; the proportional term responds immediately to changes in height error but is insensitive to how rapidly the error is changing. If the proportional gain is set high the steady state error will be small, but stability will be degraded and the response will tend to be oscillatory. The second term is derivative action, this adds an extra term that is proportional the rate of change of the error. It will improve high frequency and transient response but will highlight high frequency noise. The final term is integral action; this term removes steady state errors and improves low frequency response. However this then degrades stability and phase margins.

The overall function is:

$H(s) = K_P (1 + K_D.s + K_I/s)$

Where the terms are defined above.

5.1 Real world control

The above equation is for an ideal controller, this needs to be implemented in a real world system. This could be either done with analogue components or in the digital domain in a micro controller.
To realise this in analogue components, an integrator and differentiator need to be made of op-amps, resistors and capacitors. The following diagram shows a suitable circuit to implement an integrator.

Analogue integrator.
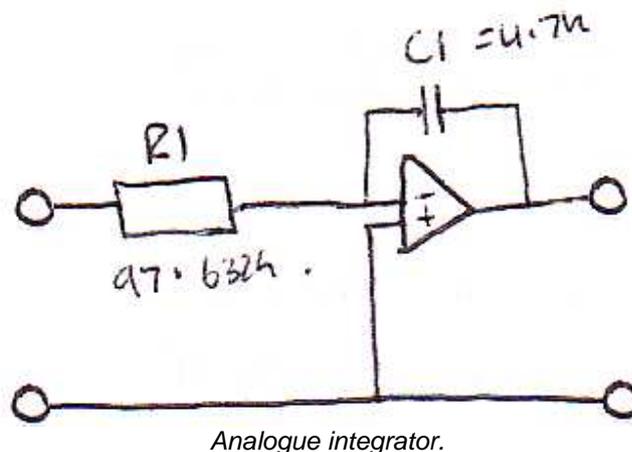
In the digital domain the integration and differentiation is carried out in discrete steps.

An algorithm to integrate would be as follows:

Integral   = (old error + new error)/2 * time period
Differential   = (new error - old error) / time period
Proportional   = new error

Where the old error is the error from the previous loop.

This introduces an error that is dependent upon the period, although, as the system will be fairly slow, and the sampling rate quick the error should be small. An example of this can be found in the program listed in the appendix.

6.0 Motion Simulation and Controller Design

To design a controller, a mathematical model of the boat was needed. This could then be simulated in a math package such a Math Lab. The fundamental principle the model is built upon is Newton second law, F = ma.
First a coordinate system was constructed, taking the rear hydrofoil as the origin, with positive up and forward. The diagram below shows all the forces that the boat is subjected to. They can be split into three main groups, weight forces from the boat and sailor, hydrodynamic forces from the foils and aerodynamic forces from the sail and rig. A pitching moment up is considered as positive.
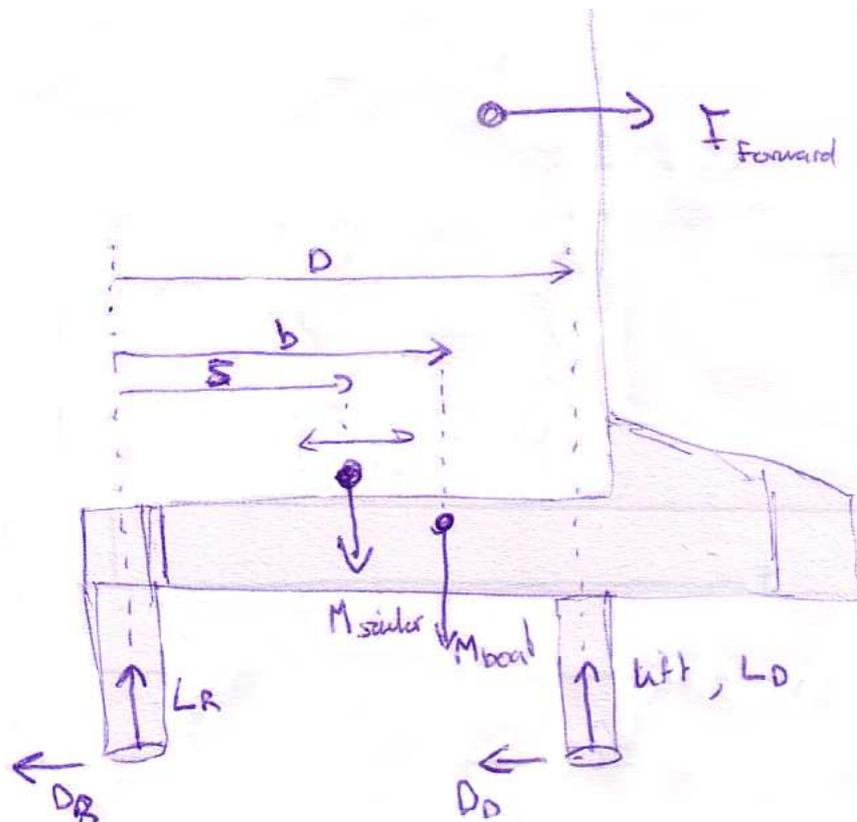

Diagram of forces on the boat.

6.1 Forces from foils: Lift

To calculate the forces from the foils a model of the foil needs to be constructed.

From aerodynamics, lift: $L = ½ \rho v^2 S C_L \alpha$

C_L is dependent upon the actual foil shape. The choice of foil shape will be discussed in the hardware section, so here I will limit myself to saying I used a NACA 64 412 aerofoil. The graph on the last page, in appendix 4, shows the plot of C_L against α. The line is almost

straight, and so can be approximated with a standard straight line equation reasonable accurately. The lift coefficient for this section is approximated by the following equation:

$C_{LH} = 0.127 \, \alpha + 1.6$

Note that even at zero angle of attack the foil still produces lift. This is due to the foil being cambered.

Sections used on the dagger board and rudder are different. The lift coefficient value for the rudder section is:

$C_{LR} = 1.225 \, \alpha$

For the Dagger board section:

$C_{LD} = 0.127\alpha$

These are un-cambered sections and so at zero angle of attack the lift is zero. The above equations are enough to be able to calculate the lift forces.

6.2 Forces from foils: Drag

It is also necessary to be able to calculate the drag from the foils to calculate pitching moments and estimate forward velocity. Only drag from the foils is considered; it is assumed that the boat is flying so parasitic drag from the hull is not included in the calculations (although the extra lift that the hull generates will help get the boat airborne). The drag equation is similar to the lift equation:

From aerodynamics drag, $D_p = \frac{1}{2} \, \rho \, v^2 \, S \, C_D \, \alpha$

Again the coefficient C_D needs to be modelled for the simulation. The drag coefficient is made up of two parts, the form and induced drag. Form drag is caused by the action of the foil in the liquid and is a buy product of the lift producing process. Induced drag is caused by the high pressure liquid below the foil flowing round the end of the foil to the low pressure, upper side resulting in a vortex from the foil tip. The total drag coefficient is given by:

$C_{D \, total} = C_{Dp} + D_{Di}$

To model the form drag, curve fitting is used. The C_{Dp}/α curve are approximately an X^2 curve. The following graph shows the actual curve (plotted badly by x-cell) and the fitted curve. The actual curve plotted from experimental data is shown in appendix 4. I played around with the constants until I got a reasonable match.
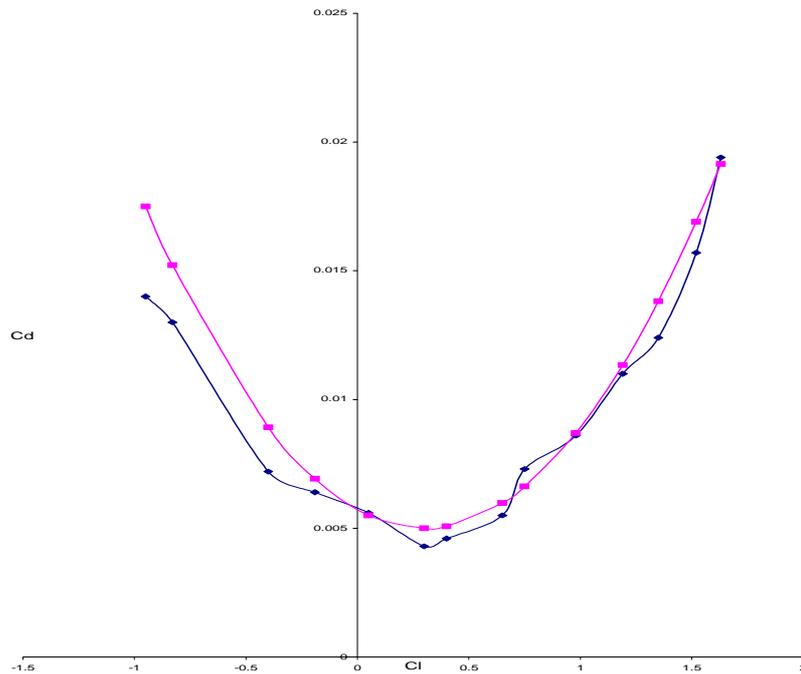
Approximation of NACA 64 421 section

Purple is the fitted curve, while blue is the actual curve.

The equation of the fitted curve for the drag coefficient of the hydrofoils is a follows:

$C_{DH} = [(C_{LH} - 0.3)^2 / 125] + 0.005$

As can be seen, this is a function of C_{LH}, and so the final drag coefficient equation is:

$C_{DH} = [(0.127 \, \alpha_H + 1.3)^2 / 125] + 0.005$

The induced drag is given by:

$C_{Di} = C_L^2 / \pi \, AR$

And so the total drag from the hydrofoil is:

$D_H = D_p + D_i$

$= \frac{1}{2} \rho \, v^2 \, S \, \alpha_H \, [(0.127 \, \alpha_H + 1.3)^2 / 125 + 0.005] + (0.127 \, \alpha + 1.6)^2 / \pi \, AR$

A similar process is carried out for the vertical foils, a NACA 64 012 section is used for the dagger board. The C_{LD} can then be plugged into the form drag equation to give:
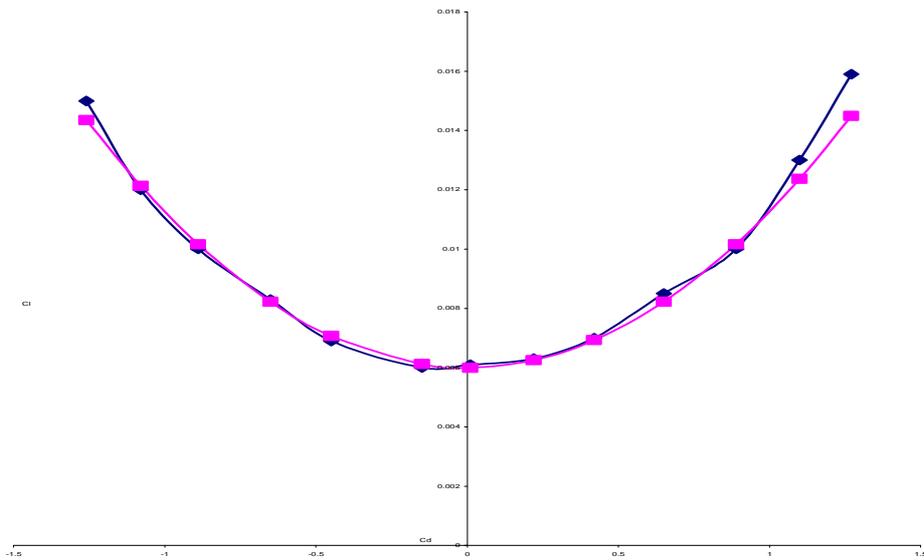
$C_{DD} = [(0.127 \, \alpha_D)^2 / 125] + 0.005$

12
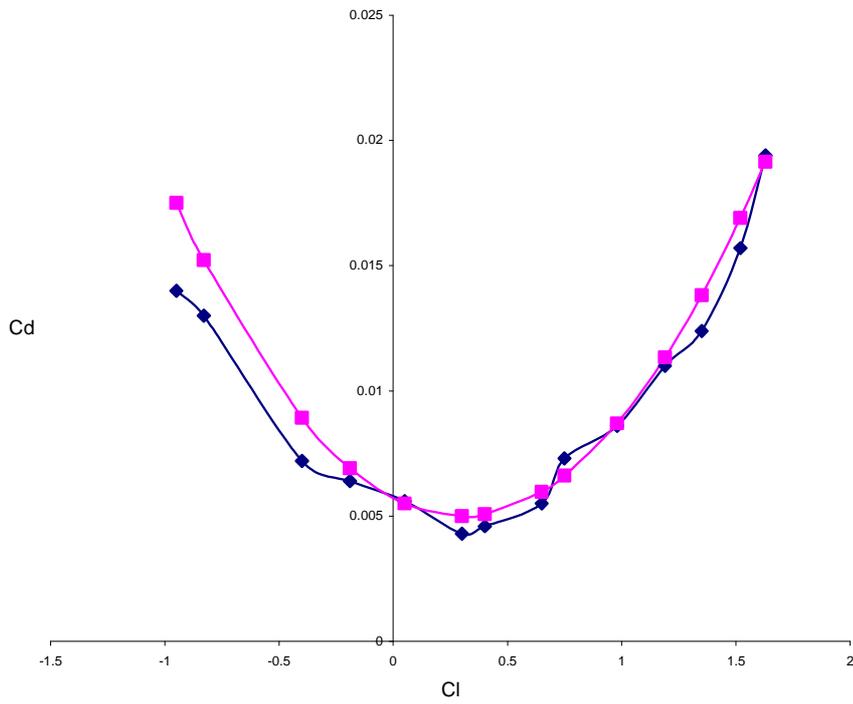
Approximation of NACA 64 012 section

Similarly for the rudder, which uses a NACA 0012 section the following expression is obtained:

$$C_{DR} = [(0.233 \, \alpha_R)^2 / 125] + 0.006$$

Approximation of NACA 0012 section

The induced drag form the vertical foils is assumed to be zero since as the foils are arranged in T configuration there will be little flow around the ends. However the drag from the vertical foils does depend upon fly height. As the boat lifts out the water less of the vertical foils will be in the water so drag is reduced. This is reflected in reduction in length.

This is implemented by the following equation:

Area,   S = length submerged * width
         S = (length - fly height) * width

Summary

Lift generated by the hydrofoils:

$L_{DH} = ½ \rho v^2 S_{DH} (0.127 \alpha^2 + 1.6 \alpha)$ - lift from hydrofoil on dagger board

$L_{RH} = ½ \rho v^2 S_{RH} (0.127 \alpha^2 + 1.6 \alpha)$ - lift from hydrofoil on rudder

$L_{T =} L_{DH} + L_{RH}$ - total lift

The drag from the foils is given as:

$D_R = ½ \rho v^2 S_R \alpha_R [(0.233 \alpha_R)^2 / 125 + 0.006]$ -drag from rudder

$D_D = ½ \rho v^2 S_D \alpha_D [(0.127 \alpha_D)^2 / 125 + 0.005]$ -drag from dagger board

$D_{RH} = ½ \rho v^2 S_{RH} \alpha_{RH} [(0.127 \alpha_{RH} + 1.3)^2 / 125 + 0.005]$ -drag from rudder hydro

$D_{DH} = ½ \rho v^2 S_{DH} \alpha_{DH} [(0.127 \alpha_{DH} + 1.3)^2 / 125 + 0.005]$ -drag from dagger hydro

$D_T = D_R + D_D + D_{RH} + D_{DH}$

6.3 Weight forces

The masses of the sailor and the boat are considered as a two point mass at set coordinates. The masses of the boat and sailor are taken as 30Kg and 70Kg respectively.

6.4 Sail Forces and Moments

The horizontal forces form the rig are directed at roughly ninety degrees to the boom, the horizontal, z direction force from the sail is counter acted by the skill of the sailor and so is not considered in this model. The Y component is the forwards force on the boat. This force is offset high up so it causes a pitching moment as well as forwards force. In windsurfing especially, this is known as mast foot pressure and can be thought as pushing the mast down. The net affect in this application is the amount of lift each foil needs to generate will vary according to wind strength and the point of sailing. To be able to predict the affect of this moment the pitching of the boat is incorporated into the simulation by taking moments about the two foils to calculate the extra lift they will need to generate. The extra lift has to be generated by the front foil mainly, and will be at its greatest sailing downwind. This is the main reason why the front foil is larger than the rear.

Therefore the force exerted on the front hydrofoil is as follows:

$-M_{Boat} . c - F_{Y sail} .d - F_{DH} . a = 0$

F_{DH} = -[M_{Boat} .c + $F_{Y\ sail}$] / a

The force exerted on the rear hydrofoil is calculated by taking moments about the front hydrofoil:

-M_{Boat} .(a - c) + $F_{Y\ sail}$ .d - F_{RH} . a = 0

F_{RH} = -[M_{Boat} .(a - c) - $F_{Y\ sail}$] / a

Where a, b c and d are dimensions defined in the diagram of the boat.

Now all the forces are known, Newton's second law can be applied to calculate the accelerations.

The forwards acceleration, a_x is given by: $a_x = (F_{sail} \sin \beta\ D_T) / M_{total}$

The vertical acceleration a_y is given as: $a_y = (L_T / M_T) - g$

These equations are in standard state space form, and so can be simulated easily in Matlab.

6.5 Simulation construction

The simulation was carried out using Simulink, a plug-in for Matlab. Each part was split into a separate block to make the simulation more readable. The main block consists of the controller, boat dynamics and the feedback loop. Below is a screen shot of this.
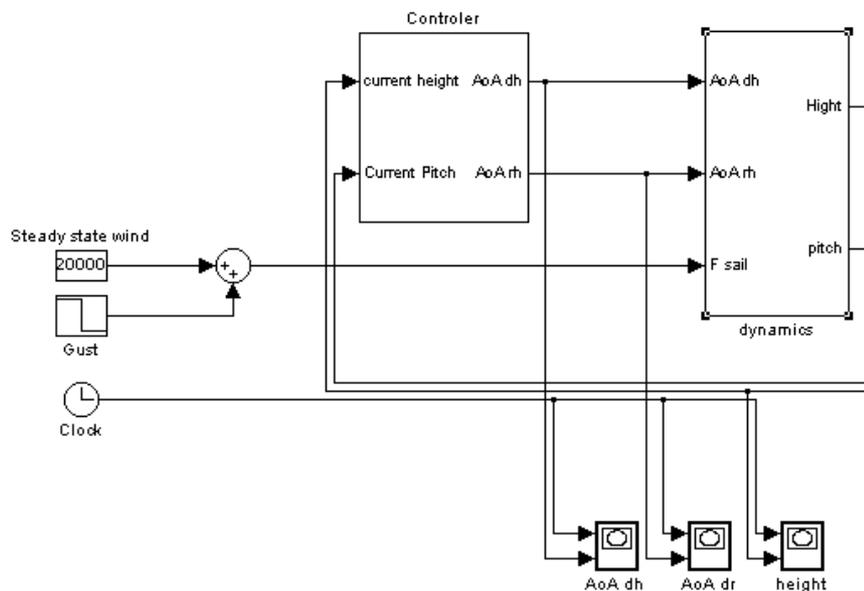
Overall structure of the simulation.

On the left is the wind speed input with the addition of a gust input. This is so that the transient response of the system due to changes in wind speed can be studied. Below the dynamics block diagram expanded to show more detail.
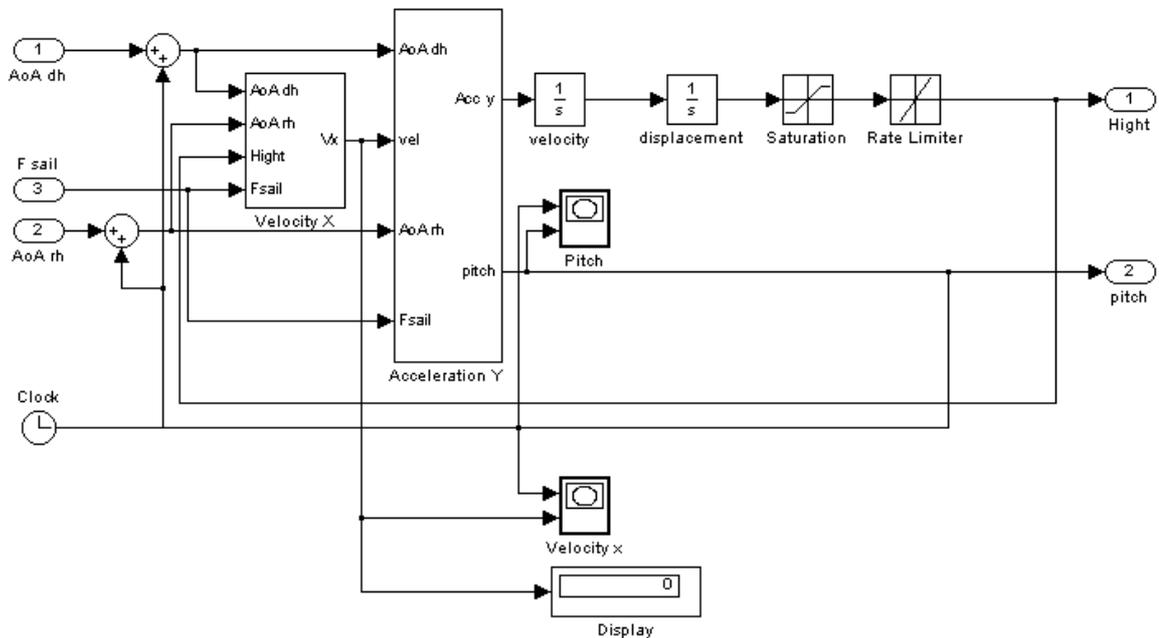
Structure of dynamics block.

From the equations the various accelerations can be calculated. The horizontal acceleration is calculated from the drag equations with inputs from the wind speed and angle of attack of the foils. This acceleration is then integrated to give the horizontal velocity. The vertical acceleration is calculated from the horizontal velocity and angle of attack of the foils. The controller is two standard P.I.D. controllers, one for the height and the other for the pitch. The block diagram of this is below.
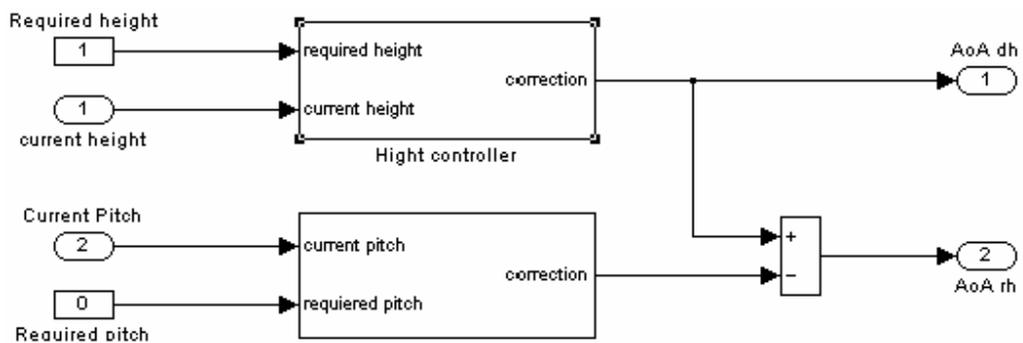
Structure of the twin P.I.D. controllers.

The height controller controls both the foils, while the pitch controller just controls the rear foil. It could be modified slightly so that the pitch controller influences both foils, but in opposite directions. The diagram below is the structure of each controller.
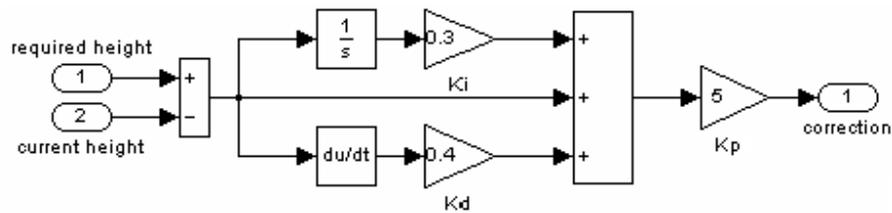
Detailed view of the height controller.

There are three constants, K_p, K_i and K_d. These are the controller parameters which are tuned to give the required response.

7.0 Hardware

The hardware consists of five major parts; the sensors, controller, memory, actuators and foils. A suitable system needs to be devised to measure or calculate the position of the boat above the water. This is then linked to a microcontroller which performs calculations to control the servos. The servos are connected to the foils via push rods. Each of these areas are now discussed in detail.

7.1 Sensors

Design brief: devise a system that produces an electrical signal proportional to the distance between the boat and the water. It must be robust since its working in a harsh environment, but also retain accuracy.

There are several different ways that this could be achieved. Each is discussed in the following sections.

Mechanical Arm with electrical sensor:

This would be similar the system that is used on the prowler. Instead of the wand connecting to a control cable, it connects directly to a potentiometer or a grey coded wheel with a light gate. This system would be easy to implement since the mechanics of it are fairly simple. It would be easy to make the arm fairly robust, but there would always the danger that it could be damaged in some way. Also the interface between the arm and the electronics would have to carefully designed so that there's adequate waterproofing. The cost of implementing this system would be low at around £5.

Metallic strip:

Two metal strips, say tin foil, would run down a foil. The resistance between the two strips would change as the level of the water varied. This could be measures with bridge circuit to give a signal for the microcontroller. I carried out tests in a bath with two strips of tinfoil attached to a piece of MDF board. I found the resistance very erratic. I next soldered a 1K resistor between the strips to remove any stray voltages. The resistant measurement was then much more stable and changed by about 30Ω per metre. I was concerned that water with different salt levels would produce different resistance measurements, so I made a saline solution and tested the same strips in it. The resistance was about 18Ω, significantly less. This would mean that each time the boat was used the sensors would have to be calibrated which is far from ideal. There is also the problem of the foils strips getting damaged and significant production issues that would have to be resolved before this system would work. I don't think this method would be suitable for this project.

Accelerometers:

The basic premise behind this type of sensor is that if you know all the accelerations that the craft undergoes you can calculate its velocity and position through numerical integration. Three accelerometers would be needed to measure vertical accelerations and pitch. The advantages with using these sensors are that there are no moving parts or external hardware to get damage. Also no modification to the boat would be needed unlike the wand sensor. The downside to using accelerometers is the cost and accuracy. The accuracy to which the microcontroller is able to determine the height is largely dependent upon the accuracy of the numerical integration algorithm. There would need to be no significant drift after about an hour since races are about an hour long. For the next race it could be reset to remove any errors. To cost of a pair of accelerometers is £30.

Ultrasound:

This was the first type of sensor that I considered. This works on the basis of timing how long a sound wave takes to travel to, bounce off and return from a surface. You could have the emitter/detector mounted on either the foils, looking up at the water surface, or on the boat looking down. I acquired a working circuit of a parking radar for a car to test out the principle and it worked fine. The only problem was with waterproofing the emitter/detector. Due to capsizes and spray the transducer needs to be totally waterproof, the problem being that you can't get waterproof transducers! I tried looking for underwater transducers, such as you would get for medical ultrasound equipment but I was unable find a source. I decided to give up on this approach because of this.

This meant I had to choose between the accelerometer and the wand sensors. I eventually chose the accelerometer since it is a much more elegant solution to the problem. It means there is no messy hardware that has to attach to the boat, just a circuit board. The next section looks at the implementation of the accelerometer.

Accelerometer circuit:

Referring to the data sheet in appendix 4, the circuit below was taken.

FUNCTIONAL BLOCK DIAGRAM
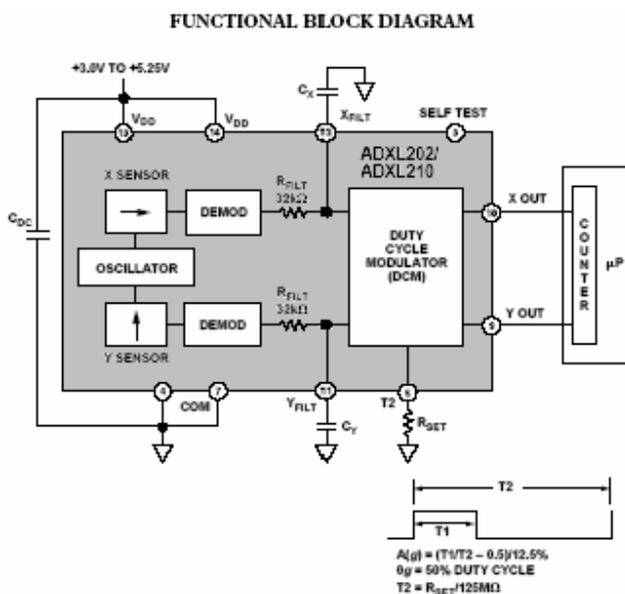
The accelerometers come in a surface mount package. For testing I attached it to strip board with the other components required. The two white filter capacitors are for a low pass filter. As the motion at the boat is fairly slow and the sampling frequency is 50Hz I selected the filter to remove frequencies higher than this. The values of C_x and C_y are 0.01µF. The resistor R_{set} sets the frequency of the output wave form. The way the program works, this needs to be much higher that the sampling frequency since the program has to read a few pulses to sync. I selected R_{set} to be 125Ω so produce an output frequency of 1KHz. As can be seen the only

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other connections are power, ground and signal lines. An opto-isolator is also used to protect the accelerometer from the microcontroller.
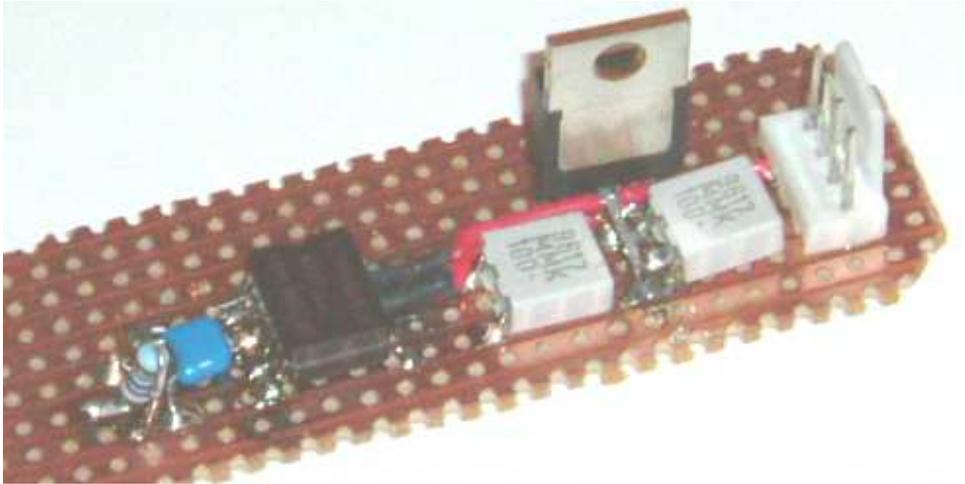
The accelerometer circuit; The black package on the left is the dual accelerometer package. There is also a power regulator on board. The 4 connections are: 5v, GND, signal 1 and signal 2. On the left is the resistor for setting the output frequency.

On studying the accelerometer data sheet, I found a suggested use for them. It had a example of a pitch measurement circuit. It works on the basis that if you align the accelerometer axis with the earth gravitation it will measure 1g. if you then rotate it 90^0 it will measure 0g. This means that the angle the accelerometer is at can be calculated. The problem comes when the boat is accelerating forwards, this will cause the accelerometer to measure this as well, causing a false pitch measurement. To counter act this, two accelerometers are used facing in opposite directions with their outputs averaged giving the pitch of the boat.

7.2 Controller

Both analogue and digital controllers were considered as a means to build the controller. For a digital controller the microcontroller circuit is very simple. It has to provide I/O pins, a clock and a power regulator. The circuit to do this is shown below:
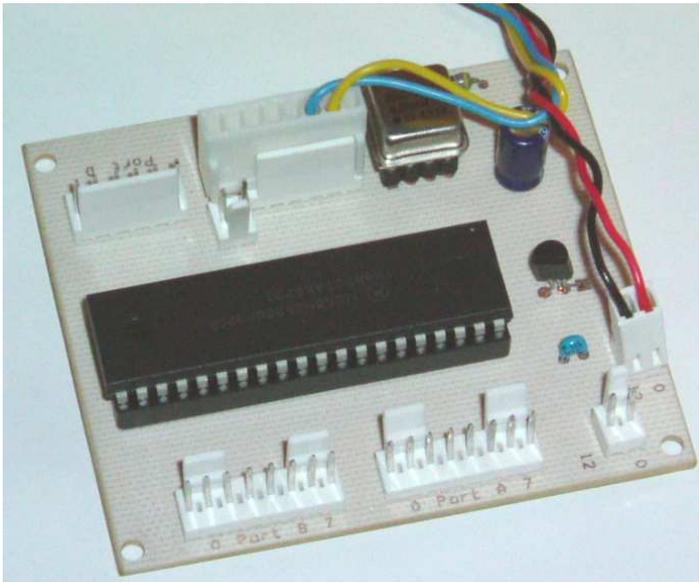
The Motorola MC68HC908 GP32 microcontroller on a PCB. The crystal can be seen at the top and there is an onboard power regulator on the right. All 5 ports are available on pins. Ports A and B are to be used for the memory interface, while ports C and D are used for I/O for the sensors, servos and reset switches.

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For an analogue circuit integrators and differentiators need to be built using discrete components, like op-amps, resistors and capacitors. I designed the following circuit to carry out two steps of integration to calculate the displacement from the accelerometers, and then a further integrator and differentiator to calculate the P.I.D. terms.
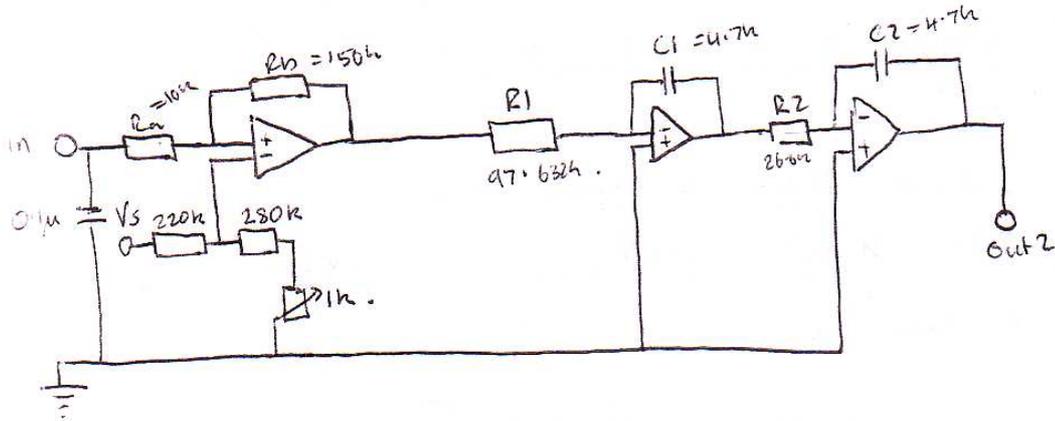
Analogue controller.

The problem with implementation the controller this way is accuracy. All of the components have a tolerance, and so your 1k resistor may actually be 1010Ω. This would impose serious design issues. A second problem is drift in the components over time, and different temperatures. This is very difficult to design for and so I decided that this approach would not be suitable in this particular situation. If different sensors were used, for example the wand, where you have position initially this type of controller would be more suitable because the errors are not so important.

7.3 Memory

So that the simulation can be validated, data needs to be collected regarding the motion of the boat. This data needs to be stored on, say a flash EPROM so that it can be recalled later into a pc for analysis. Atmel manufacture a chip with 2 megabits of memory that costs about a pound. This would be linked to the MCU via port A and B. Every time the program repeats the main loop it would store the position and orientation of the boat. Unfortunately I ran out of time to implement this.

7.4 Actuators

The actuators used are model servos. They were selected because they accept a simple P.W.M signal, they are very robust, they are available in a range of sizes and they are relatively cheap. Selecting a servo is a different matter though since there are a vast range of sizes and powers available. Estimating the power required is not easy. If the pivot on the foil is placed about the ¼ cord, there will only be very small hydrodynamic force on the foil, but there is the inertial of moving the foil and water and also the friction in the system to take account of. The only simple way of doing this is by trial and error, starting with a servo of moderated quality and replacing it if it's not up to the job.
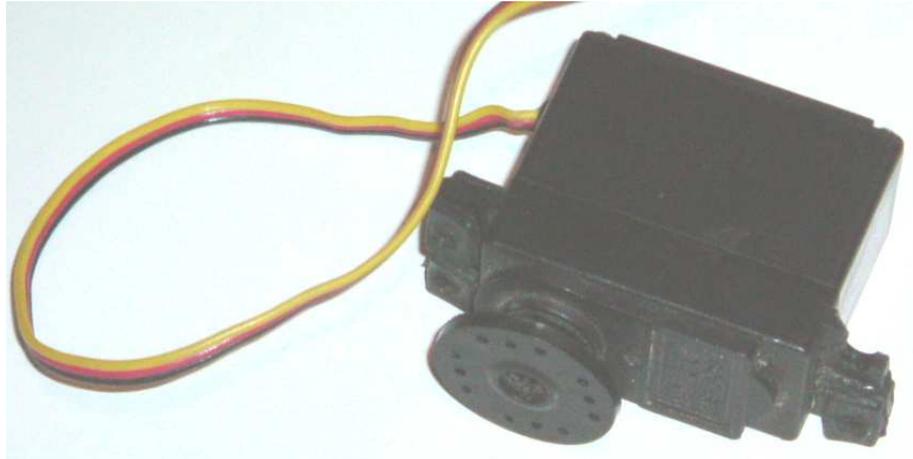
A standard model servo that could be used.

7.5 Foils

As discussed above I will use a moulding process, where the foil is moulded in two half's in female mould, and then joined together afterwards.

First I constructed some moulds by routing out grooves in MDF board to a rough section. I next made a metal template to use as a guide. Using this template to shape epoxy filler I made the rough routed section into a better aerofoil section. A few more layers of epoxy and polyester filler and a lot of sanding were used to obtain a good section. Three moulds were made two for the hydrofoils as threes a top and bottom, and one for the vertical foils.

The first attempt at moulding wasn't very good. I used silicon grease as a release agent and this wasn't good enough. Areas of the moulding stuck to the foil.

My second attempt I covered the mould in sticky back plastic, the type that's used for covering books, etc. I also introduced the use of balsa wood; a thin layer of it between the carbon layers was designed to make the laminate stiffer. I was concerned that the carbon would be too fragile to be used on its own.

The lay-up consisted of: 200gms unidirectional carbon
400gms unidirectional carbon, half layer
1/16 balsa layer, selected for hardness
200gms unidirectional carbon

A small amount of epoxy filler was used to fill in gaps around the edges of the balsa. In all about 100gms of epoxy was used per 900mm length. Once it had been laid up, a sheet of Clingfilm was added, then a specially shaped piece of wood that fitted the inside shape of the foil was placed on top. To compress the laminate together all my text books were piled on top. The pictures on the next page first show the mould then the laminate.

This is the mould for the lower hydrofoil section. At the trailing edge it is actually convex due to the camber on the section.
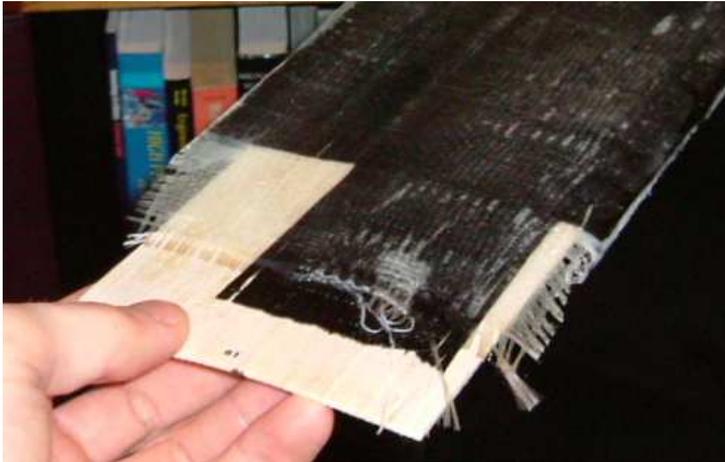
The lay-up is clearly visible here, before trimming. Note the half layer of 400gms carbon.

This is the final section. The different layers can just be made out. Note how the balsa finishes before the trailing edge. This is because the trailing edge is very thin.

8.0 Software

The PID controller described earlier needs to be implemented in software for a microcontroller to run. I only had experience with assembly and C so I decided to use C code since it would be much quicker to program and easier to understand and modify.

The first thing I did was to write a P.I.D. algorithm. The proportional part is simply the error multiplied by the constant K_p. To calculate the derivative, two variables are used height_error and old_height_error. Height_error is the new calculated error, while old_height_error is the error from the last loop saved at a memory location. Since calculating the derivative is simply the rate of change of error, the change in error is multiplied by the sampling period, or loop period. Example code is below:

```
dif_height = (height_error - old_height_error)/period;
```

A similar approach is adopted for the integral part. Integral action is calculating distance travelled, or area under the graph. In discrete time you are concerned with strips under a graph, so to find the area of the strip the length of the two sides are summed, and then

dived by two. This gives the average height. This is then multiplied by the period again to give the area. Example code is below:

```
int_height += (old_height_error + height_error)*(period/2);
```

The += means that the new value of int_height is the old value plus the new error.

This was then combined into a function to calculate the control value.

```
signed char calculate_pitch_control_value(void)
{
        signed char
        pitch_error;            /*PID controller for pitch*/
        signed char
        dif_pitch;
        signed char
        calculate_pitch(void);

        pitch_error = calculate_pitch();

        int_pitch += (old_pitch_error + pitch_error)*(period/2);

        dif_pitch = (pitch_error - old_pitch_error)/period;


        old_pitch_error = pitch_error;       /*update pitch error*/

        return ((kp*pitch_error) + (ki)*(int_pitch)+kd*(dif_pitch));

}
```

The above function calculated the pitch control value. First some local variables are initialised. There scope is only for this function. Next the pitch error is calculated. A different function is called here to do this called `calculate_pitch();` and is described later on. The two variables, `int_pitch`, `dif_pitch` are then calculated and the pitch error is then updated for the next loop. The returned value from the function is a sum of the three parts of the P.I.D. controller multiplied by their respective coefficients.
There is a similar function for the height P.I.D. controller.

The next two functions are concerned with calculating the displacement and pitch of the craft, the first being to calculate the fly height of the boat. The output of the accelerometer is a modulated square wave; the period stays constant while the on time of the pulses changes with acceleration. Consult the section on the accelerometers for exact details.
To read this pulse chain the microcontroller must first synchronise with the pulses. To do this the following code is used:

```
while(b_PC3==1)   /*waits for a low value until proceeding*/
        {};
while(b_PC3==0)   /*waits for a high value until proceeding*/
        {};
while(b_PC3==1)                   /*increases acc_new until */
        {                         /*input pulse goes off*/
          acc_new ++;
        }
```

It Waits until the pulse goes from a low state to a height state, and then back to a low state before it starts counting. The final while statement keeps incrementing the variable `acc_new` until the pulse goes off again. A similar piece of code is used for the calculate displacement function.

To calculate the displacement of the boat, the accelerations are integrated twice using the same principles as before. The following code is the complete function for calculation the displacement of the boat.

```
signed char calculate_displacement(void)
{
      unsigned char acc_new = 0;


      while(b_PC3==1)    /*waits for a low value until proceeding*/

       {};

      while(b_PC3==0)    /*waits for a high value until proceeding*/
       {};

      while(b_PC3==1)                  /*increases acc_new until */
       {                               /*input pulse goes off*/
         acc_new ++;
       }
                                       /*perform integration*/

      displacement += 2*(vel_old)*(period / 2) + (acc_old +
                        acc_new)*(period)*(period)/4;

      acc_old = acc_new;               /*update acc_new*/
                                       /*update vel_old */

      vel_old += (acc_old + acc_new)*(period / 2);


      return (displacement);
}
```

Again there are some variables that store information about the last integration loop that are updated each loop.
To calculate the pitch a similar synchronisation routine is used to read the accelerometer. Two variables are calculated, `Acc_forwards` and `Acc_backwards.` These are the measured acceleration forwards and backwards. If these two accelerations are equal, zero is returned since the pitch is zero else a small amount of calculation is performed then the pitch value is returned. This function is shown with the rest of the program.

The subroutines perform the majority of the calculations in the program. To tie all the subroutines together and perform the timing and servo control the main loop is used. First it initialises data direction registers and timer registers, after that it enters into a continuous loop. In this loop a timer counts up, that when the timer overflow bit is set the program generates the output for the servos, reads the accelerometers and then calculates the control value for the next loop. Using a timer is the only practical way of ensuring that the output for the servos is accurately timed at 50Hz.

9.0 Results

9.1 Simulation:

Only results from the simulation are available since there was insufficient time to conduct sea trials, although they will be conducted at a later date.
The simulation was run many times, while adjusting the controller parameters. The selected plots below are of a 20 second simulation with a lull at 7 seconds.

Outputs from the simulation.
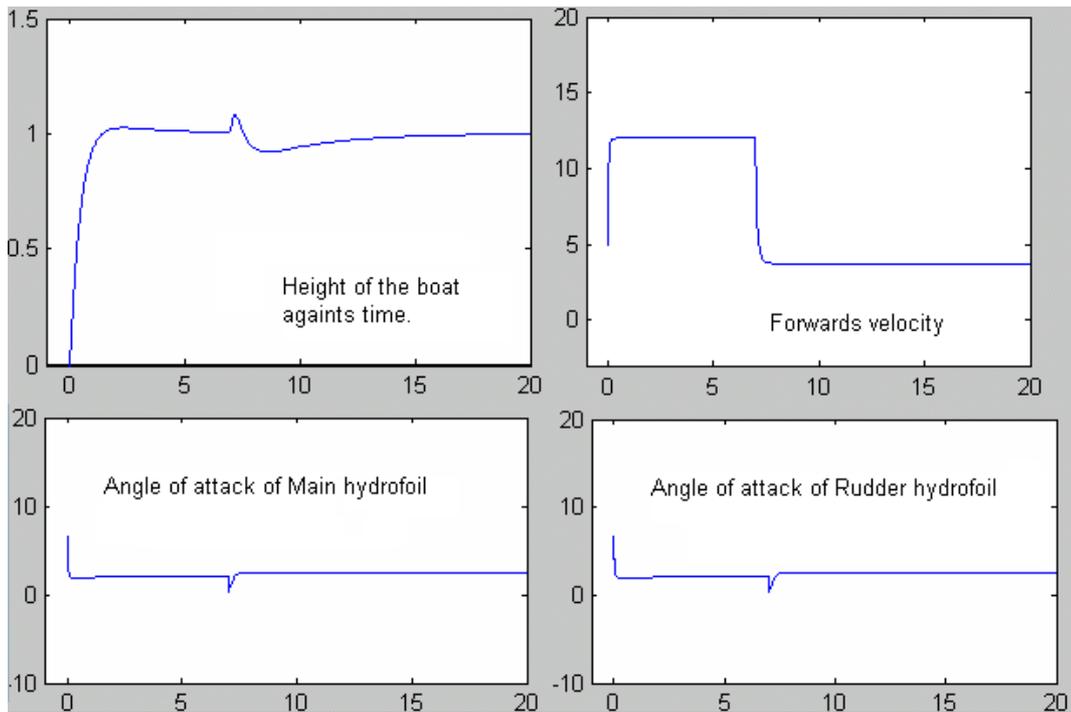
The height is well controlled, and does not displaying any tendency to oscillate. Once all three controller parameters were close to the ideal value the simulation wasn't that sensitive to small changes in a particular parameter. This is good because if the plant changes a small amount, e.g. the sailor moving, the control characteristics shouldn't be badly affected.

The lull at 7 seconds causes the boat to rise up a small amount due to less pressure from the rig. This was expected since this affect is observed on the Australian moths. This goes some way to validating the structure of the simulation, but it can not fully validated until sea trials are carried out and experimental data is obtained.

One purpose of the simulation was to asses the dimensions of the Australian foils. This was done by running the simulation repeatedly while changing the size of the rear foil until both foils were at the same angle of attack. I reasoned that it would be desirable for the two foils to be at a similar angle of attack so one is not creating more drag thank the other. From this I found that the rear foil should be increased from 530mm to 720mm.

9.2 Sensors:

The first experiments to be carried out were for the ultrasound module, but as it was decided from an early stage that this type of sensor wouldn't be suitable I will not include it here.

The second experimental work that was carried out was for the tin foil strips. Below shows the setup for this; a bath was used, with and without salt added to the water. A 1K resistor was attached across the strips and a multi-metre was used to measure the resistance.

The setup for testing metal strip sensors.
The left picture is the strips taped to the MDF board,
while the right picture shows a close up of the strips.

There was a linear relationship between the length of foil exposed to the water and the resistance, but there was also a relationship between the resistance and the salt content of the water. This would obviously be a problem if you went from fresh water, where there is relatively little salt, to the sea where there are high levels of salt. The system would have to be recalibrated each time it was used, although it would be possible to do this automatically.

The accelerometer performed as the data sheet stipulates.

10.0 Discussion

The simulation shows that a controller can be designed fairly easily but for the simulation to be of any use though it needs to be validated. From the study of the Australian moths is clear that a proportional controller should be able to control the moth to some degree of success. However in the simulation it was found not to be possible, and the dynamics seemed to be a little. I think that a dampening term may have been missed out in the model, and hence the fast response. A second factor not included in the simulation was the input from the sailor, he/she was modelled as a fixed mass; in practice the sailor is able to shift their mass around the boat. The mainsail is constantly adjusted which is also not modelled; as the sail produces a considerable moment the sailor may be subconsciously using this to help control the boat.

While modelling the foils it was assumed the whole foil pivoted to adjust the amount of lift that it produces. It may not be possible to construct a pivot strong enough to take the forces from the water. Even if it is, it still may be too susceptible to damage from the sailor during capsize or launching. This area will need some development and testing before is robust enough for prolonged use. A different option would be to have a flap, similar to the Australian design. This is known to work, although the foil won't be as efficient due to the extra drag the gap and hinge cause.

During a late stage of this project a different system was conceived. Instead of using a T foil configuration, a ladder type structure could be used. A few small foils, say 15-20cm span are attached up the dagger board and rudder. When all the foils are in the water there is excess lift. As the boat rises up they start to exit the water meaning less lift is produced. This system would self regulate in height and need no control system. A down side to this is the short foils will have a greater induced drag and so they won't be as efficient. Also the system may want to oscillate between two of the small foils.
A similar system could be a V shaped foil attached to the dagger board which, as the boat rises up, the ends break through the surface. Again this would be self controlling; as the boat rises up less of the foil is under the water and so less lift is produced. Again there is a downside; will be more drag due to the longer foils and the may be cavitation along the foil due to air being sucked down from the surface. This could be stopped by having perpendicular plates attached to the foil at regular intervals, but again this would increase drag.

11.0 Suggestions for further work

The major design work has been completed; the main task now is to tie the whole system together. While the program is working it needs to be fine tuned for it to perform accurate integration and control. The sensor input and actuator outputs need to be calibrated as well.

One major area that I wasn't able to carry out much work on was the memory interface. Data needs to be collected so that the simulation can be validated. This area has been researched; the hardware is simple, just connect the wires. The software needs a subroutine added which writes the address and data values to a port.

Instead of using a microcontroller to control the foils an old laptop could be used. These are available on eBay for around £30 and so are very cost effective. Matlab could be used to handle the control; with some suitable software it could be more flexible than a microcontroller.

Once all the hardware is working together extensive sea trials need to be carried out to validate the model, and turned the controller until good response is achieved. The hardware could be then developed for better performance, say by having better foils and actuators.

12.0 Conclusions

The performance gains that are available from hydrofoils are evident and should be exploited as much as they can. This sort of performance boost doesn't come alone every day. The may be a new sail, or a slightly quicker hull, but these are a couple of percent increase in performance, not twenty percent.

An electronic control system has the potential for the most efficient design in performance terms. However it may be too complex to be reliable on an every day basis. Compared to a system that has no moving parts is mort susceptible to breaking however good it is.

During this project I have come to the conclusion that while electronics is a possible way to control a moth, there may be ways more suited to this application.

13.0 References

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UK Moth web site, www.int-moth.org.uk

Fastacraft website, www.fastacraft.com

14.0 Appendix 1: Designs

List of successful designs of the international moth. Reproduced from www.int-moth.org.uk/designsSP.htm

Magnum 8
Year designed: 1988
Results Achieved: Europeans/nats 88/89
Comments: U-section hull with low rocker, successful design for it's time. Probably the most common 'first moth'. Can still be fast in light winds.
Approx value today: £400-£800

Blitz
Year designed: 1989
Results Achieved:
Comments: Good all round boat, especially in planning conditions. Could prove to be a bit difficult as a first time boat.
Approx value today: £300-£600

Ghoul 2
Year designed: 1989
Results Achieved: race wins at Europeans/nats
Comments: Similar to Magnum 8 in performance terms, space frame with wingtip shroud base, torpedo foredeck, and no flares. May prove a bit difficult as a first Moth. Waterline width of 442mm.
Approx value today: £300-£600

Gentleman Jim
Year designed: 1989
Results Achieved:
Comments: similar to Mag 8 waterline width of 550mm
Approx value today: £300-£600

Axeman 1
Year designed: 1989
Results Achieved:
Comments: The first of the narrow boats, slightly more freeboard, suitable for a first time boat for experienced sailor (best if buoyant tramps). Waterline width 350mm.
Approx value today: £400-£700

Magnum 9
Year designed: 89/90
Results Achieved: worlds 90 nats 90/91
Comments: The first narrow boat in the Magnum saga, a narrow slab sided box design with most of them being fitted with buoyant wings. Only suitable for first time moth for experienced sailor. Waterline width of 356mm.
Approx value today: £700-£1000

Ghoul 3
Year designed: 1990
Results Achieved: 2nd Worlds 90 (only just!)
Comments: Low freeboard design with fine bow sections and small flares. Carbon/Kevlar

foam sandwich construction. Difficult first time moth. Waterline width of 320mm.
Approx value today: £600-£800

Axeman 2
Year designed: 1990
Results Achieved:
Comments: Similar to Axeman 1 but with a wider stern to stop transom sinking during tacking. Suitable for a first Moth, if buoyant tramps and experienced sailor. Waterline Width of 330mm.
Approx value today: £500- £800

Axeman 3
Year designed: 1990
Results Achieved:
Comments: Extremely narrow, high foredeck with flares. Ply carbon, glass, foam construction, fast upwind in light to medium winds. Not suitable for a first Moth. Waterline width 240mm.
Approx value today: ?

Pearce 6
Year designed: 91/92
Results Achieved:
Comments: Based on the Pearce 5 with additional freeboard at the stern, also similar to Magnum 9. Suitable first narrow Moth. Waterline width 370mm.
Approx value today: £500-£1000

Axeman 4
Year designed: 1992
Results Achieved:
Comments: Similar to axe 2 but more refined and narrower transom. This was the design the next few years of Australian boats were based on. Suitable first moth for experienced sailor.
Approx value today: £600-£1000

Skippy
Year designed: 1992
Results Achieved: worlds 96 Europeans 94/97 Nats 95/96/97/98, 3rd nats 2001
Comments: A design with clean lines and hard U sections and low rocker. Raised foredeck. Carbon/Kevlar foam sandwich construction. Waterline width of 348mm. probably the most successful design of recent times.
Approx value today: £2500 - £4000

Note: all moths from Skippy onwards, provided they have carbon mast and buoyant wings seem to be reasonably easy to sail in light to medium conditions, probably due to their easily driven hull shapes and light weight. If the sailor is experienced, it may be worth considering a narrow boat to start with (although this may be more expensive). There have been a fair few examples of this working successfully over the last few years.

Magnum 9.5
Year designed: 92
Results Achieved: Worlds 93, Europeans 92, Nats 92/93/94
Comments: A design with clean lines, bulbous bow and concave topsides to reduce waterline width and topside weight. 1.5mm ply Carbon/Kevlar construction. Waterline width

of 316mm.
Approx value today: £1600-£2500

Axeman 5
Year designed: 1993
Results Achieved:
Comments: Similar in shape to the Axeman 4 but having a narrow V shape transom
Approx value today: £1500-£2800

Magnum 9.9
Year designed: 1993
Results Achieved: 3rd Nats
Comments: Similar to the Magnum 9.5 but having a narrower transom and winged rudder making it slightly faster in light winds and more controllable in strong winds. Waterline width of 336mm.
Approx value today: £2500-£3300

Axeman 6
Year designed: 1995
Results Achieved: 1st Nats 1999, 2nd nats 2000, 1st nats 2001, 3rd Worlds 98
Comments: Very rounded sections compared with its predecessors done in an attempt to reduce wetted surface area. Carbon/Kevlar foam construction. Very stiff hull, rounded under bow goes very well in a breeze and sea.
Approx value today: £3000- £4500

Skippy 2
Year designed: 1996
Results Achieved: 6th Nats 2000, 6th 2001
Comments: Hard chine, no flares, quick in some conditions. As yet not proven.
All carbon, very light.
Approx value today: up to £3000

Hungry Tiger
Year designed: 1997 (Mark Thorpe Aus)
Results Achieved: Worlds 98, Aus nats 98/99,1st UK nats 2000, 2nd UK nats 2001
Comments: Clean hull form. Similar to Skippy but with fine bow and vertical topsides.
Approx value today: £4000 upwards

Axeman 7
Year designed: 1999
Results Achieved: 3rd Nats 99, 3rd nats 2000, 5th nats 2001
Comments: Cross between axe 5 and axe 6, but slightly narrower. Fine pintail stern, fine entry, rounded under bow leading to flatter stern. Reduced flares at bow compared to previous Axeman design
Approx value today: £4000 upwards

15.0 Appendix 2: Class rules

15.1 Summary:

1. Sail area of 8 square metres
2. length of 3355mm
3. max width of 2250mm
4. max mast length of 6250mm
5. max luff length of sail 5185mm
6. no trapezes, movable boards etc

15.2 IMCA Rules

30/31st October, 1999

Authority international Yacht Racing Union, 60 Knightsbridge, London SW1 X 7JX Date of International Status. 1st September 1972

1. General

The International Moth is a single-handed development class boat. The Intention of these class rules is to give the designer and builder the fullest liberty in design and construction, within these rules to develop and produce faster boats.
The official language of the class is English And in the event of a dispute over translation, the English text shall prevail.
These rules are complementary to the measurement form. Any interpretation shall be mane by the l.Y.R.U which may consult the International Moth Class Association. (IMCA).
In the event of discrepancy between the rules and the measurement form, the matter shall be referred to the l.Y.R.U.
In countries where there is no National Authority, or where the National Authority does not wish to administer the class. its function as stated in the rules, shall be carried Out by l.M.C.A or it's delegated representatives I National Associations).
Neither the l.Y.R.U nor the IMCA accept legal responsibility in respect of the rules, or any claim arising there from.

2. International Class Fee

The amount of the I.C.F. may be reviewed by the l.Y.R.U on recommendation of l.M.C.A.
The l.M.C.A is responsible for the collection of the l.C.F and the distribution of l.C.F receipts on the above basis.
The l.M.C.A may delegate its responsibility to collect the l.C.F and issue receipts to National Associations.
The I.C.F is payable by the Builder on each boat built whether or not it is subsequently measured and registered. Payment shall be made direct to the National Authority or its delegated Representative (National Association I. which shall issue an endorsed I.C.F receipt. The l.C.F receipt shall be delivered by the builder to owner on sale of the boat.
I C.F receipts shall be valid only if mane out on official forms issued by the l.Y.R.U. The purchase price in each case represents the Proportion of the I.C.F. due to the I.Y.R.U. and the IMCA. The National Authority or its delegated Representative National Association, may charge an additional sum not exceeding the administration cost of carrying out this function.

3. Registration and Measurement Certificate

No boat is permitted to race in the class unless it has a valid measurement certificate.
The owner shall be a fully paid up member of the relevant l.M.C.A National Association.
Each National Authority or its delegated Representative National Association) shall .issue sail numbers which shall be consecutive and the number shall be preceded by the official National letters. A National Authority or its delegated Representative snail only .issue a sail number on receipt of evidence that the l.C.F has been paid.
No two boats in the class registered in the same country shall have the same name.
The certificate is obtained as follows:
- The owner or builder shall apply to the appropriate National Authority or its delegated Representative (National Association. for a sail number enclosing the l.C.F receipt, and at the same time submit the proposed name(s) of the boat. The National Authority or its delegated Representative shall enter the sail number in the l.C.F receipt.
- The owner or builder shall obtain a measurement form from the National Authority or its delegated Representative, and shall have the boat measured by a measurer officially recognised by the National Authority. The completed form shall be supplied to the owner of the boat.
- The owner shall send the completed measurement form to his National Authority or its delegated Representative together with any registration fee that may be required. On receipt of this the National Authority or its delegated Representative may issue a certificate to the owner.
Change of ownership invalidates the certificate but shall not necessitate re-measurement the new owner may apply to his National Authority or its delegated Representative (National Association for a new certificate. returning the old certificate together with any re-registration fee required and stating the necessary particulars. A certificate shall then be issued to the owner.
It is the owners responsibility to ensure that his boat, spars, sails And equipment comply with the class rules at all times. Alterations and replacements shall be measured. When relevant, by a measurer recognised by the National Authority or its delegated Representative (National Association), who will, if necessary, endorse the measurement certificate accordingly, and shall notify the National Authority or its delegated Representative where this would apply.
Notwithstanding anything contained in these rules the l.Y.R.U or the National Authority or its delegated Representative (National Association) shall have the power to refuse to grant a certificate to, or withdraw a certificate from arty boat.
The l.M.C.A shall obtain at regular intervals from each National Authority or its delegated Representative (National Association details of sail numbers and l.C.F receipts issued.

4. Measurement

Only a measurer officially recognised by the National Authority or its delegated Representative shall measure a boat. its spars. sails and equipment, And shall sign the declaration form that they comply with the class rules.
The measurer shall report on the measurement form anything which he may consider to be unusual or to depart from the intended nature of the boat or to be against the general interest of the class and a certificate may be refused, even if the specific requirements of the class are satisfied.
A measurer shall not measure a boat, spars or sails or equipment owned, designed or built by himself, or in which he is an interested party or he has a vested interest.
New or substantially altered sails shall be measured by a measurer who shall stamp or sign and date the sail near the tack. The details shall be recorded on the certificate and the entry signed by the measurer or secretary of the National Authority or its delegated Representative (National Association) (National Association).
All boats, spars, sails and equipment shall comply with the current rules.
All boats, spars, sails and equipment shall be liable to re-measurement at the discretion of a race committee or the National Authority or its delegated Representative (National Association).

5. Identification Marks

The class emblem shall be a representation of a Moth and shall conform in shape and size to the pattern held by the I.Y.R.U. copies may be obtained from I.M.C.A or National Authority or its delegated Representative (National Association).
The sail number and national letter(s) of the boat shall be cut into, or marked indelibly on the hull, aft on the port side in figures not less than 3Omm high. These shall not be removed for the life time of the boat.
The sail number, national letter(s) and class emblem on the sail shall conform with I.Y.R.U Yacht Racing Rule 25. letters and numbers shall be not less than the following sizes: Height: 250mm Width: 165mm (excluding one and letter I) Thickness: 35mm Space between adjoining letters and numbers: 50m4m, (For sails measured, before 1st March 1973,the minimum height shall be 230mm and minimum width (150mm).
All emblems, numbers and letters shall be off a durable material and securely attached.

6. Hull

The overall length of the hull, excluding attached rudder fittings and stem fittings shall not exceed 3355mm measured between perpendiculars with hull level transversely and waterline horizontal. No attempt at increasing waterline length shall be made by fairings comprising part of, or attached to, rudder or stem fittings.
The overall beam shall not exceed 2250mm.
Catamaran or multi-hull configurations are prohibited. There' shall be no visible air gap dividing the boat longitudinally throughout its length when afloat upright, fully equipped but without crew. In the case of a boat with a flexible or hinged transom this test shall be made with the transom in the fully raised position.
Within the static water plane area there shall be no hollow in the hull more than 75mm in any section closer than 2700mm from the aft perpendicular as described in rule 6(i). The reference line for this hollow shall be a string line stretched tightly around the underside of the hull from points on the static waterline either side of the hull and the string line shall be at right angles to the hull. The static water plane area shall be defined as the area bounded by the extremities of overall length and maximum waterline beam when afloat upright, fully equipped, but without crew.

7. Buoyancy

Boats shall have not less than two separate buoyancy tanks or bags attached firmly to the hull which together must be sufficient to float the boats own weight plus 75kg, approximately level when capsized or full of water, and which, with any one tank flooded must be sufficient to float the boats own weight, plus 10kg. If a measurer cannot ascertain compliance with this Rule by visual inspection, he shall undertake a buoyancy test to so satisfy himself.
The measurer shall satisfy himself that the buoyancy compartments are effective by means of flotation or air test. (As a guide, leakage should not exceed 5% of volume of tank in half an hour).

8. Spars.

The overall length of mast shall not exceed 6250mm.
Measurement Bands, not less than 15mm wide shall be marked on the spars so that they are clearly discernible when racing. The inside edges of these bands define the limits to which the sail may be set.
The distance between the bands shall not exceed 5185mm.

9. Sails

The boat shall only carry one sail. No extra sail shall be on board when racing.

The sails and spars shall be measured in accordance I.Y.R.U "Measurement and Calculation of Sail Area". The I.Y.R.U. Sail Measurement Instructions shall not apply. The measured and calculated area shall not exceed 8.00m2 metres area, except that, Clause 3.2.5(b) of the I.Y.R.U Measurement and Calculation of Sail Area shall not apply.

Only the area of that part of the spars that will not pass through a ring 9Omm internal dia, shall be included.

For a sail which encloses the mast, an area equivalent to the length of the luff multiplied by 50mm shall be excluded.

For a sail which encloses the boom an area equivalent to the length of the foot multiplied by 9Qmm shall be excluded.

Battens shall extend not more than 150mm from the sail. No attempt at increasing sail area shall be made by the number or size of the battens used.

Where the sail is set on spars, no part of the sail luff shall extend beyond the lower edge of the upper mast band, or below the upper edge of the lower mast band.

International Moth sails do not require a boom band to be declared, and shall be measured in accordance with I.Y.R.U Measurement and Calculation of Sail Area clause 3.3. (Clause 3.2.3 shall apply for area of main triangle). The owner shall declare the max sail foot length (BC) and shall mark this declared foot length clearly and indelibly on the foot of the sail at the tack in figures at least 10mm high. The BC measurement shall be less than the measured distance from outside the cringle to outside the clew. when the sail is stretched Out and pegged down for measurement.

10. Crew

There shall only be one person on board when racing. The righting moment of the helmsman's weight shall only be transferred to the sail through the hull or sheet or similar, in which case it shall be through blocks attached to the hull.

11. Prohibitions

Moving or detachable seats and trapezes.

12. Anchor

An anchor need only be carried when specifically prescribed in the sailing instructions.

16.0 Appendix 3: P.I.D. controller program for Motorola Hc08 microcontroller

```c
#include "hc08gp32_r.h"

signed char     kp = 1;
signed char     kd = 1;
signed char     ki = 1;

signed char     period = 1;            /*loop reputation period*/
signed char     desired_height = 1;    /*set ride height of*/
                                       /* the boat*/
signed char     length = 1;            /*length between the*/
                         /*accelerometers and the front foil*/

signed char     vel_old = 0;

/*variables to use in integral part of program. initialise initial
values for the vertical velocities*/

signed char     acc_old = 0;

/*initialise initial values for the accelerations*/

signed char     int_height = 0;
signed char     old_height_error = 0;

signed char     int_pitch = 0;
signed char     old_pitch_error = 0;

signed char     displacement = 0;


signed char     zero_g;
signed char     reset;
signed char     CV_front = 0;
signed char     CV_rear = 0;
unsigned char   count = 4;




void main()
{

  DDRA = 0xFF;                         /* PORTA as output to memory*/
  DDRB = 0xff;               /* PORTB output for address bus to memory*/
  DDRC = 0x00;           /* PORTC input to servos and memory control*/
  DDRD = 0xff;

  CONFIG1=1;                           /*kill the dog*/



  zero_g = calculate_pitch();

  T1SC=0x20;             /*reset T1 Status and control register*/
  T1MODH=0xFF;             /*set Timer modulo registers to 0190*/
                           /*in hex so timer will count from
                           /*0-50us continuously changed this*/
```

```
T1MODL=0xFF;
T1SC0=0xFF;                          /*Reset T1 Channel 0 and */
                                     /*1 status and control registers*/
T1SC1=0xFF;
b_1TSTOP=0;              /*start timer*/




  while(1)
    {
     if (b_1TOF==0)              /*if timer overflow bit not set*/
       {}

      else                      /*this next part performs the P.W.M*/
        {                       /*output the servos*/
          b_1TOF=0;
          if(count ==1)
            {
              if (CV_front != 0)
                {
                  b_PC4 = 1;
                  CV_front --;
                }
               else
                {
                  b_PC4 = 0;
                }
            }

          else
            {

              if (count == 0)
                {
                  count = 4;
                  if (CV_rear != 0)
                    {
                      b_PC5 = 1;
                      CV_front --;
                    }

                   else
                    {
                      b_PC5 = 0;
                    }
                }

              else
                {
                  count--;
                }

            }
        Main_loop();
        }
    }
}
```

```
char main_loop()                    /*main interrupt loop,*/
                                    /*executed every 20ms*/
{
                                    /*forward reference for subroutines*/
  signed char calculate_displacement(void);
  signed char calculate_height_control_value(signed char);
  signed char calculate_pitch_control_value(void);

  signed char CV_height;
                                    /*variable declaration*/
  signed char CV_pitch;

  signed char control_value;
  signed char pitch;


  if (b_PC0 == 0)
                                    /*  reset routine */
    {
      control_value = 0;
      old_height_error = 0;
      displacement = 0;
      vel_old = 0;
      acc_old = 0;
      zero_g = calculate_pitch();
    }

  else

    {

        pitch = (calculate_pitch() - zero_g);

        CV_height = calculate_height_control_value(pitch);
        CV_pitch = calculate_pitch_control_value();

        CV_front = CV_height - CV_pitch;
                  /*calculate actual control values for each foil*/
        CV_rear = CV_height   + CV_pitch;


        return(0);

    }
}


signed char calculate_height_control_value(signed char pitch)
{
        signed char                 height_error = 0;
            signed char                 dif_height = 0;
                                    /*PID controller for height*/
        signed char                 height_control_val = 0;
            signed char
        calculate_displacement(void);

        height_error = ((calculate_displacement() - desired_height)
+ pitch*length);
        int_height += (old_height_error + height_error)*(period/2);

        dif_height = (height_error - old_height_error)/period;
```

```
        height_control_val =
((kp*height_error)+(ki)*(int_height)+kd*(dif_height));

        old_height_error = height_error;                    /*update
height error*/

        return(height_control_val);
}


signed char calculate_pitch_control_value(void)
{

            signed char            pitch_error;
                    /*PID controller for pitch*/
        signed char            dif_pitch;
        signed char            calculate_pitch(void);

        pitch_error = calculate_pitch();

        int_pitch += (old_pitch_error + pitch_error)*(period/2);

        dif_pitch = (pitch_error - old_pitch_error)/period;


        old_pitch_error = pitch_error;
                        /*update pitch error*/



        return((kp*pitch_error)+(ki)*(int_pitch)+kd*(dif_pitch));

}


signed char calculate_pitch(void)

{
        unsigned char Acc_forwards;

        unsigned char Acc_backwards;

          while(b_PC1==1)
        /*waits for a low value until proceeding*/
          {};
          while(b_PC1==0)
        /*waits for a high value until proceeding*/
          {};
          while(b_PC1==1)
            {
              Acc_forwards ++;
            }


        while(b_PC2==1)
          {};
          while(b_PC2==0)
          {};
          while(b_PC2==1)
            {
```

```
                Acc_backwards ++;
          }

        if (Acc_forwards == Acc_backwards)
         {
           return(0);
         }
        else
         {
           return(20/(Acc_forwards - Acc_backwards));   /*the value 20
is a representation of 2*g. this will need to be changed*/
         }
}


signed char calculate_displacement(void)        /*gets vertical
acceleration and returns displacement input old displacement*/
{
        unsigned char acc_new = 0;
             /*this reads new acceleration*/

        while(b_PC3==1)
        /*waits for a low value until proceeding*/
         {};
        while(b_PC3==0)
        /*waits for a high value until proceeding*/
         {};
        while(b_PC3==1)
        /*increases acc_new until input pulse goes off*/
         {
           acc_new ++;
         }

        displacement += 2*(vel_old)*(period / 2) + (acc_old +
        acc_new)*(period)*(period)/4;

        acc_old = acc_new;
        /*update acc_new*/

        vel_old += (acc_old + acc_new)*(period / 2);
             /*update vel_old */

        return (displacement);
}
```

17.0 Appendix 4: Data sheets

17.1 ADXL202 (accelerometer)
17.2 AT49F002 (Flash memory)
17.3 OPA 344 (op-amp)
17.4 SFH 608 (opto isolator)
17.5 MC68HC08GP32 (microcontroller)
17.6 Motorola application note AN1215/D (P.I.D. routines for microcontrollers)
17.7 NACA 0012 aerofoil chiastic
17.8 NACA 64 412 aerofoil chiastic

18.0 Appendix 4: Technical Specification