

**GENG5512 MPE Engineering Research Project Part 2
Final Report**

**Developing Active Hydrofoil Stabilisation with Autonomous
Steering**

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DECLARATION OF CONTRIBUTION

You must provide the required information below and sign this declaration page. When you submit your report, you are confirming that the information provided is correct. See Section 2.3 of this guide for more information.

My contribution

Provide details here of your contribution to the project and the contribution of others.

Self:

- Selection and procurement of electronics
- Implementation of key functionality and control systems
- Testing and tuning of control systems

Others:

- Construction of external components
- Modification of hull and installation of physical components
- Implementation of key functionality and control systems
- Testing and tuning of control systems

Use of AI tools

I have used AI tools in the preparation of my report: Yes/No

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The above information is correct, and the attached work submitted for assessment is my own work and that all material drawn from other sources has been fully acknowledged and referenced.

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Supervisor confirmation

To the best of my knowledge, the student's contribution outlined above is correct.

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Abstract

This project aims to develop active stabilisation and autonomous steering for a fully submerged hydrofoil system, which should be able to pitch out of the water and prevent itself from tipping while steering itself towards its intended destination.

This task has been undertaken because active hydrofoils will be the next major step in improving water vessels. Passive hydrofoils have been used to increase speed and efficiency, and vessels such as a jet-skis, typically have excellent manoeuvrability on their own. By combining these advantages into a single system, marine vessels globally can be improved with little to no effect on their performance, making them more efficient and sustainable.

The hull has been procured from an external supplier to maximise performance and reduce the design requirements so more attention can be devoted to the development of control systems. The project uses some basic electronic components, including an Inertial Mass Unit (IMU), Ultrasonic Sensors (USS), and a Global Positioning System (GPS) module to gather information on the boats position and orientation, and a microcontroller is used to process inputs and drive outputs from the implemented control system computations.

The outcome of the project aims to see a fully functional hydrofoil stabilisation system, and an autonomous steering system that implements the hydrofoils to bank the boat, allowing for significant manoeuvrability.

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Nomenclature

IO (or I/O)	- Input/Output
GPIO	- General Purpose I/O
PID	- Proportional, Integral, Derivative
PI	- Proportional, Integral
PD	- Proportional, Derivative
IMU	- Inertial Mass Unit
GPS	- Global Positioning System
PWM	- Pulse Width Modulation
UART	- Universal Asynchronous Receiver-Transmitter
I2C	- Inter-Integrated Circuit
NMEA	- National Marine Electronics Association
ASCII	- American Standard Code for Information Interchange

1. Introduction

Climate change is a major issue plaguing the modern world [1], [2]. In order to combat this, greenhouse gas emissions must be reduced [1], which can be done through methods such as improved energy efficiency. The UWA Renewable Energy Vehicle (REV) project aims to pursue this, developing electric vehicles and further improvements to reach a goal of zero emission vehicles [3]. Included in this is the continued improvement of marine vessels and the development of active hydrofoil technology.

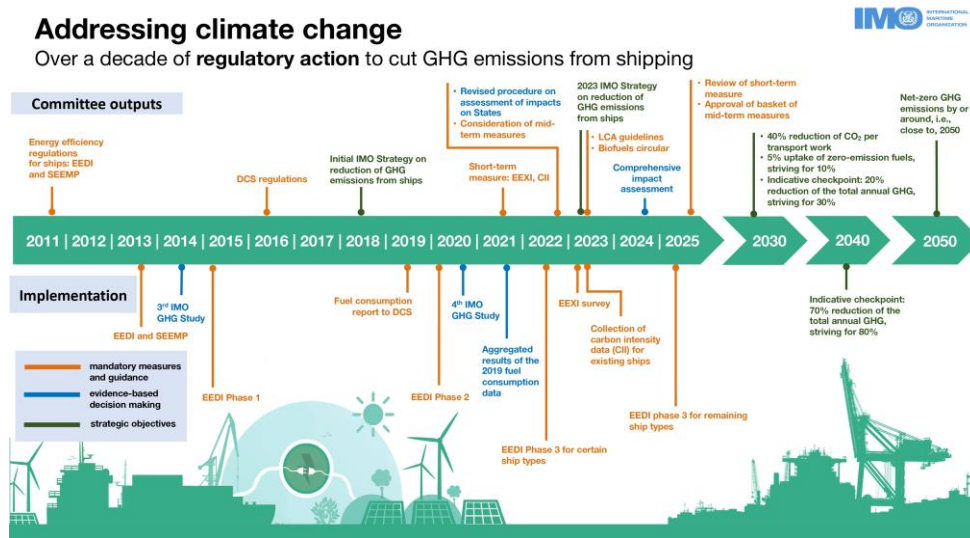


Figure 1: IMO Milestones for Reducing Greenhouse Gas Emissions from Shipping [4]

The International Maritime Organisation (IMO) has and continues to aim for increased efficiency of maritime vessels, with the end goal of zero emission vessels [4]. This is why the REV project has undertaken research into hydrofoils.

Hydrofoils are designed to improve the energy efficiency of maritime vessels by lifting the hull out of the water, which reduces drag due to the decreased surface contact [5]. Additionally, since the hull will no longer be in the water, there is significantly less water that must be displaced, further increasing the vessel's efficiency [6]. Passive hydrofoils have been implemented before [7]; however, their static nature results in a lack of manoeuvrability since it relies on the rudder, limiting their potential range of applications. As a result of this, research is being done into active hydrofoils in order to improve the range that their benefits can be applied to.



Figure 2: Electric Hydrofoil Jet-Ski Developed by the REV Project [8]

The REV project has endeavoured in this research previously; however, wants to further develop their systems with additional functionality to maximise their use and efficiency [3]. To develop active hydrofoils some system must be implemented to control its position and rotation. As such, research currently focuses on how this can be achieved, and how autonomous steering can be implemented to maximise its performance.

2. Project Objectives

2.1 Overall Aims

The overall goal of this project is to develop a prototype model for an active hydrofoil stabilisation system and autonomous steering implementation. For stabilisation, the prototype should be able to pitch out of the water and remain in this state for the full steering duration. Achieving this will require control systems for pitch and altitude to control the height, as well as roll to ensure the roll angle remains within a range that does not affect this ability. The implementation of autonomous steering should be able to track the position of the vessel, and steer it towards the target position without external steering inputs. This will also be done through a control system in order to ensure the target position is effectively tracked.

This project also continues from previous research [9], [10]. As such, it aims to improve on the flaws from the previous design, with the major flaws being the hull & aileron design. With improvements, the physical construction will cease to be the limiting factor, thus the project can focus on implementing effective control systems.

To achieve this the project can be broken down into the following subsystems*:

2.2 Roll Control

Roll control aims to implement effective control algorithms to prevent the vessel from tipping over during travel. This implementation should also have limited effects on other control and steering systems.

2.3 Altitude Control

Altitude control aims to achieve a state where the vessel is able to maintain itself in a foiling state. Achieving this for a certain period of time will be required to considered it capable of maintaining this state, which should be achievable while steering the vessel.

2.4 Autonomous Steering

The implementation of autonomous steering aims to be able to navigate between two points through GPS waypoint navigation. The implementation will **not** include the ability to avoid objects and/or steer around them.

*Note: The hull's construction was required for this project but will not be covered in this report

3. Design Process

3.1 Roll Control

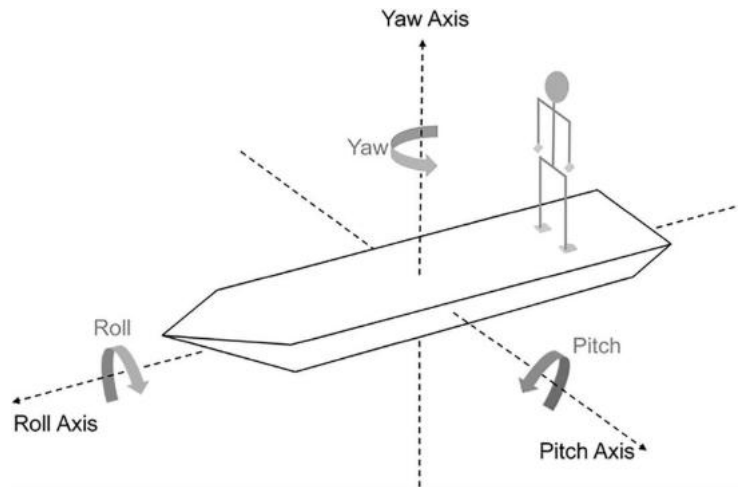


Figure 3: Diagram of a Boat's Rotational Axes [11]

3.1.1 Constraints

Due to the use of T-shaped hydrofoils, there are minimal horizontal forces applied from the physical design of the vessel. Because of this, ensuring the vessel does not roll during travel has to be done through other means [6]; in this case, some method to pivot the ailerons in order to create a force difference between the two wings.

Since the wings will be pivoted to control vertical forces, a frequency limit should also be implemented. Should a limit not be included, large back-and-forth adjustments may create large or unnecessary strain on the ailerons or adjustment device, which may result in damage much quicker than basic wear-and-tear.

3.1.2 Requirements

The process of controlling the boats roll requires sensors to measure axes, and hardware and software implementations to correct the roll when it occurs [12]. A sensor will be required to measure the roll angle so it can be fed into a control system, and this control system must then be effectively tuned to be able to adjust the ailerons to counteract the roll initially applied to the vessel.

3.1.3 Control

In order to control the system effectively, the correct control system must be used. Certain control systems may be unfeasible for the task at hand or be unable to properly correct the system under certain circumstances. The underlying control system will be required to be a closed-loop feedback system so the system can be controlled in reference to its current and target position [12]. Failing to implement this system would result in the system knowing where it needs to be, but not where it currently is so it can adjust accordingly. However, the way this feedback system is implemented can be altered based on the requirements at hand.

A fuzzy logic controller, for example, applies certain behaviour based on logical inputs [13], which may struggle with function or implementation if the required logic is too complex. A linear control system, such as a second order system could be implemented; however, these systems typically result in oscillations and steady-state error which may not work for the required level of control [14]. The control system used previously was a PID controller [9], [10], which have several benefits including their ability to adjust small errors introduced by disturbances, but can take a significant amount of time to tune to achieve this control [15].

3.1.4 Sensors

The choice of sensors will be affected by the measurements required by the control system; for roll control this will simply be the roll angle. An inertial mass unit (IMU) or ultrasonic are the two candidates for this measurement, and the final choice of these options will come from the acceptable complexity of implementation. IMUs are the standard choice for measuring angles in real-time but require calibration; ultrasonic sensors on the other hand require two to be able to determine the angle, but do not require an initial calibration to do so.

3.2 Altitude Control

3.2.1 Constraints

Since pitch and altitude will both act on the same plane, they will affect each other; thus, implementing these control loops may not be as simple as creating one loop for each parameter. Due to this, these control loops will likely require a multi-input format so these calculations can be performed together so the vessel may achieve both set-points effectively.

3.2.2 Requirements

The requirements for altitude control are very similar to those of roll control. Sensors will be required to measure the vessels positional data, however, since altitude is not an angular value, a gyroscopic sensor will not be feasible for achieving this. While this can be done with an IMUs accelerometer(s), calibration would need to be done in the water to give it the correct zero position on the y-axis. However, the calibration process can be sensitive to movement so this may result in incorrect readings during travel.

3.2.3 Control

Since altitude and pitch will be affected by each other, a more complex control system will need to be implemented. While separate control loops could be implemented for each parameter, trying to maintain a certain pitch and altitude separately may result in these loops conflicting with each other. The solution to this would be to implement some multi-input system, which would need a single output since the altitude and pitch work on the same output hardware.

3.2.4 Sensors

The most likely sensor for this application is an ultrasonic sensor, which works by emitting a sound wave and measuring the time it takes to receive the reflected wave [16]. While the readings may have problems due to the uneven surface of the water, other considered sensors were determined to be unfeasible. Pressure sensors were considered, but depth at which they will be during foiling was not considered to be great enough for them to function properly. LiDAR sensors were also considered, but refraction and scattering caused by uneven and/or cloudy water would likely result in failed readings.

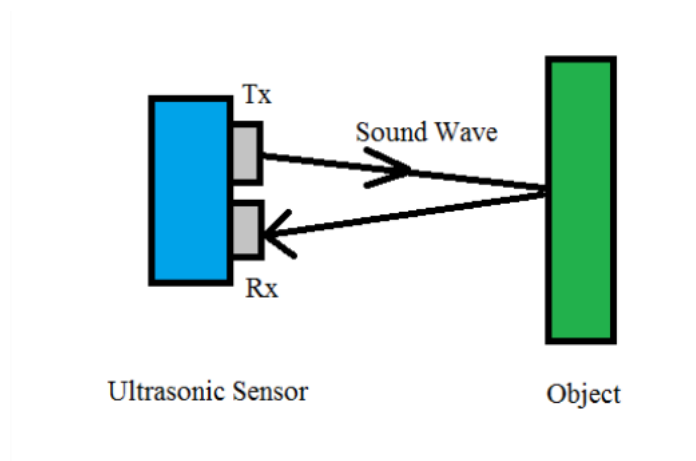


Figure 4: Working Principle of an Ultrasonic Sensor [16]

3.3 Autonomous Steering

3.3.1 Constraints

Physical obstacles will significantly impact the ability to steer autonomously since it will disrupt the planned path, requiring real-time adjustments to compensate. Other vessels or floating debris will require additional sensors and algorithms to detect and navigate these situations accordingly. Failure to do so could cause momentary disruptions, or in the worst case, damage components.

Additionally, the boat's steering precision will be limited, thus steering should be done to within a range around the target position. Forcing the boat to go to the exact position may result in it attempting to steer tighter than it is able to, or to a precision greater than required, resulting in it circling around the waypoint. To prevent this, a range should be set around the waypoint as an acceptable margin for the system to navigate to.

3.3.2 Requirements

Autonomous steering requires reliable sensors and control algorithms to ensure effective navigation. These sensors must be able to track the current position and heading, in order to compare these to the target coordinate/heading in the PID loop.

3.3.3 Implementation

Algorithms will be required to handle I/O and pathing calculations. Handling coordinate calculations is feasible through either manual coding or a library, since pathing will only involve basic geometrical calculations. On the other hand, handling data I/O may require additional technical knowledge than is feasible, thus may be more convenient to implement through a library.

3.3.4 Hardware/Sensors

In order to control steering, the current and endpoint coordinates must be known. The endpoint should be known, thus only needs to be given to the system. However, a method will be required to determine the current position and heading which can be done through either a compass or a GPS. An IMU could also be considered for this but would be limited to heading control and thus would still require additional hardware for coordinate tracking.

4. Final Design and Results

4.1 Roll Control

4.1.1 Control Methodology

To control the position of the vessel a PID control loop was chosen to be implemented. This choice comes as a result of a PID controller's flexibility, and ability to correct itself effectively when properly tuned [15].

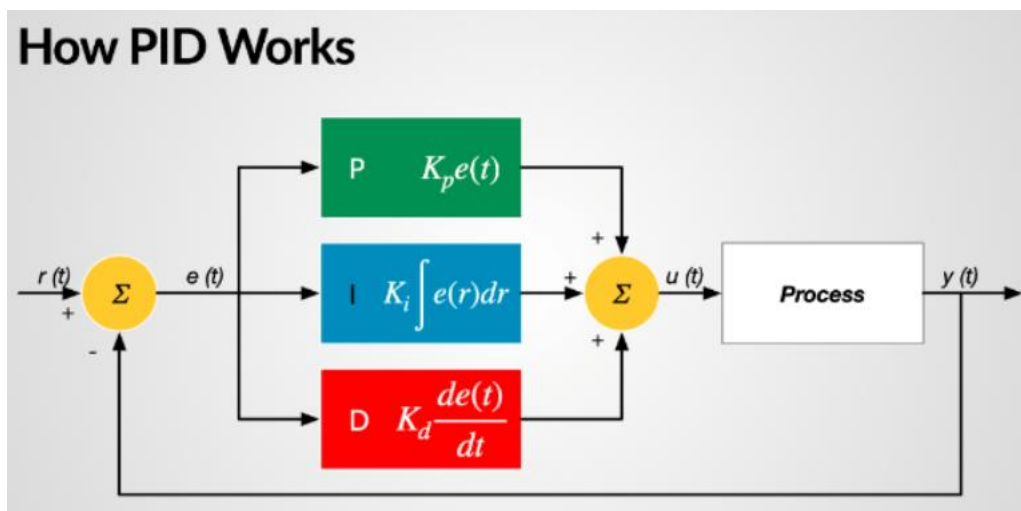


Figure 5: Block Diagram of a PID implementation [17]

The PID control loop was implemented in a standard, negative-feedback configuration, where the controller has the implemented PID functions as seen in figure 5. This allows the system to keep track of the error between the setpoint and current point and adjust accordingly based on the coefficients chosen during the tuning process [12], [15]. These coefficients are chosen through trial-and-error in order to minimise unwanted characteristics of the control response.

By selecting these parameters carefully, the system can be tuned to correct error in a certain way. The proportional parameter is a direct scaling of the current input error, which controls the immediate response to the error, being the main driver of the short-term response. The integral component takes the integral of the error value from some start time to the current time, which keeps track of the total error. This can correct any long-term error, accounting for the steady-state limitations of the proportional controller. Finally, the derivative component tracks the gradient of the response function to predict the upcoming value and act as a dampener [15]. By damping the response, overshoot can be reduced, preventing large spikes.

4.1.2 Hardware

In order to achieve the desired level of control, selected hardware must be able to measure external parameters, process data, and drive outputs which must be done reliably.

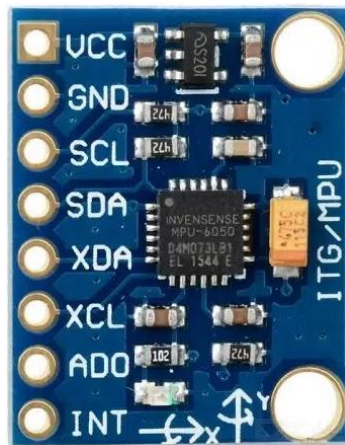


Figure 6: Picture of an MPU6050 breakout board [18]

To control rotational axes an inertial mass unit (IMU) was used to measure the angular position of the system in real-time, which was done through the use of the MPU6050 shown in figure 6. This IMU has a number of factors influencing its selection. Digital motion processing (DMP) is used on-board the IMU and allows it to perform calculations using sensor data to provide a fast and accurate output [19]. While it only has 6-axis capabilities on its own, additional sensors can be installed and implemented to take advantage of 9-axis DMP to further increase accuracy and precision if required [19].

The previously used Adafruit BNO085 IMU [9], [10] was not reused as it was noted to have problems with data communication.



Figure 7: LilyGo T-Display S3 [20]

The chosen processor for the required I/O was the ESP32, specifically, the T-Display S3, shown in figure 7. Compared the previously used Arduino Mega [9], [10], the T-Display has several benefits. The clock speed of the T-Display is 240MHz [21] compared the Arduino Megs 16MHz [22], allowing increased data processing and removing it as a bottleneck in the control systems' implementation. It also has significantly more random-access memory (RAM) allowing for more test data to be stored at a single time, and built-in wi-fi to transmit it without additional hardware. The built-in display is also incredibly useful for debugging, allowing data to be displayed in real-time without requiring a physical connection.

Due to its small form factor, however, the T-Display S3 also has significantly less GPIO pins than the Arduino Mega [22], [20], meaning that a limited number of devices could be connected. As a result, additional hardware was required to re-distribute some of the I/O.

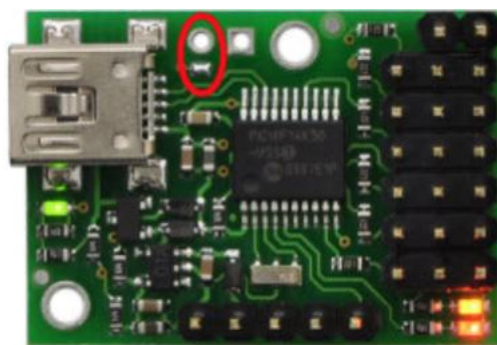


Figure 8: Pololu Micro Maestro Servo Controller [23]

The first idea proposed was to use a second T-Display device and have the two devices transfer data to via a bus. However, this approach negates the advantage of its small form factor and introduces a

second device that must be programmed. Instead, it was decided that a servo controller, shown in figure 8, would be used instead. While this does also need to be programmed, once the operating firmware and settings have been uploaded it can be implemented in the system and sent data to alter the output pulse width modulation (PWM) signals without further modification [23]. This was then used to send PWM signals to the motor and servos.



Figure 9: Picture of the DS3235 Servo [24]

PWM signals can be used to alter the power of electrical devices without changing the input voltage. By implementing this with a motor, the throttle can be controlled by altering the duty cycle of the PWM signal, allowing for active speed control [25]. A servo on the other hand, like the one in figure 9, uses a PWM signal to control its position [26] which allows it to be rotated within its range based on the data sent to the servo controller. The DS3235 was the selected servo for this design; it has a high force capability of 29kg at 5V [27], making it an excellent choice since it will ensure stability during foiling operations. Additionally, its precise resolution allows for tiny adjustments to be made [27], allowing for precise control over the vessel's axes.

4.1.3 Software

The implemented software needs to be able to steer the boat autonomously but also needs to have manual capabilities for testing and as a failsafe. This was done through the implementation of a remote control and receiver allowing for control of all external steering hardware, specifically the

FS-i6x transmitter and FS-iA6B receiver. Connecting the receiver to the microprocessor allows it to receive signals from the transmitter and send them to the microprocessor as a PWM signal, which can then be read and used to drive the relevant outputs.

Additionally, two frequency limits were introduced to prevent the software from stalling and prevent mechanical damage as a result of large forces. Firstly, the previously used loop frequency of 50Hz was re-used [9], [10], this keeps the frequency high enough for the boat to control itself but low enough for high stress to be minimized. The second limit is introduced with the remote-control reading speed. Each pulse width from the receiver has a maximum length of 2500 μ s, meaning that for all 6 required inputs the maximum reading time would be 15ms, 75% of the entire loop period. To prevent stalling, the implementation was altered to allow only one input reading per loop, dropping reading time to 12.5%.

The PID calculations were then implemented into the code as a struct and function. A struct can be declared as a custom data type, storing several different values under one label. Thus, the PID struct can be used to store all relevant PID data, including PID coefficients, I/O values, and other additional properties such as scaling and data logging. This struct can then be declared for each required PID loop, creating a simple way to store data for them separately. Furthermore, since all PID loops will have the same input parameters, the PID calculation can then be implemented as one function, rather than one for each PID loop. Passing a struct into the function allows it to be referenced for each PID loop, which can then calculate and store required values, and log relevant data points without interfering with other PID data.

4.1.4 Results

The process of testing and tuning is tedious, but essential to ensure the PID control system functions correctly. To ensure response time, steady-state error, and overshoot are kept to an acceptable level, the control system must be carefully considered, tested, and adjusted according to test results.

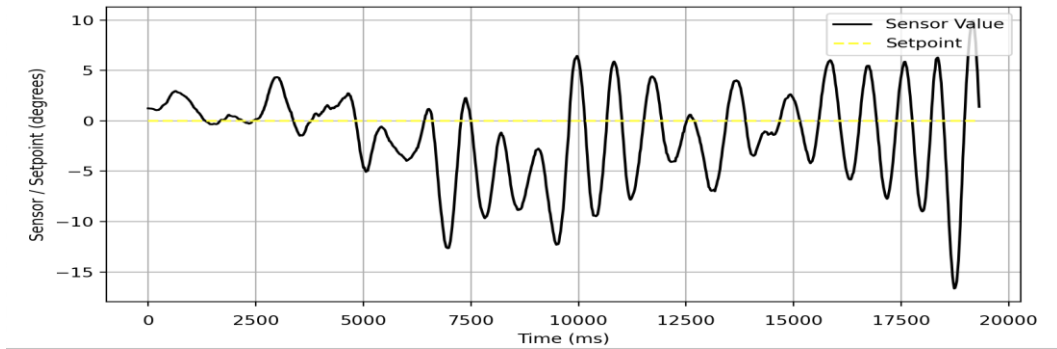


Figure 10: Roll response at P = 300

In initial tests, seen in figure 10, a simple proportional controller was implemented to test roll control capabilities. While this test managed to maintain roll within $\sim\pm 12^\circ$, this was still significant enough to affect steering and oscillated far too much to be considered stable. Further tuning was required to stabilize the roll, particularly to reduce overshoot, which was achieved through further tuning to the proportional component and the introduction of a derivative component, seen in figure 11. Additionally, these oscillations occurred around a steady-state value of the target 0° ; thus, did not require tuning to the integral component.

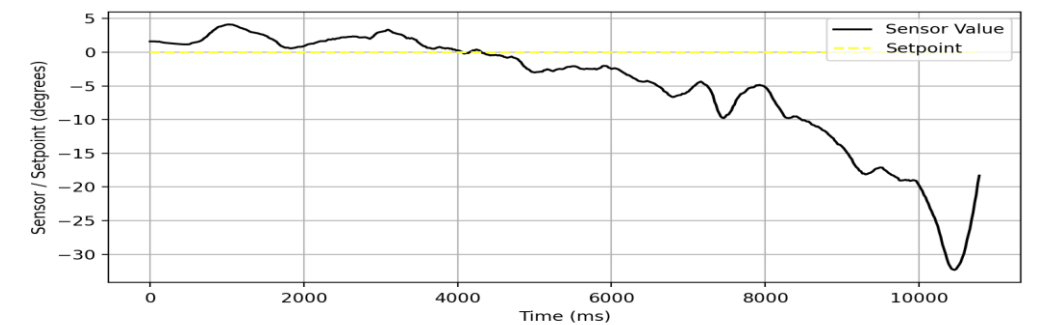


Figure 11: Roll response of Test at P = 150, D = 40

Next, the proportional controller was updated to a PD controller, in an attempt to manage the large oscillations from the previous test. The introduction of the derivative component and the decreased proportional component made a significant improvement in this, keeping the roll angle within $\sim\pm 5^\circ$ initially. After ~ 6 sec, however, the boat began rolling further, likely due to turning. Rolling during a turn is not necessarily undesired, since rolling into the turn assists in keeping the boat stable during travel, but this can be seen to slowly drift further as turning continues, eventually becoming unstable.

Since the target angle was still 0° during this process, this test still showed the system's inability to correct its roll and as such, required further adjustments to improve the response.

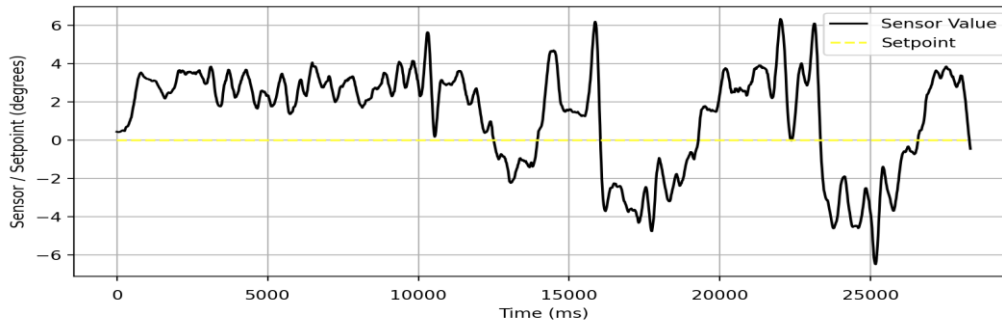


Figure 12: Test with $P = 200$, $D = 40$ with additional Parabolic Response

The final addition to the roll control system was to introduce a parabolic response function, which was implemented using fuzzy logic thus only has an effect after reaching a certain threshold. The idea of a non-linear response function is to alter the response at to require a different output magnitude at different errors, this can be seen below in figure 13.

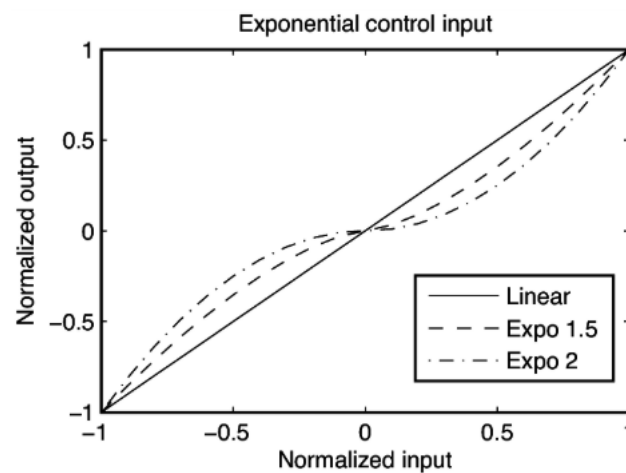


Figure 13: Normalized Exponential Scaling Function [28]

This was implemented because the system struggled to control itself at larger roll angles, so introducing the scaling function would increase the response at higher roll angles, while the smaller angle response would barely change. The response in figure 12 shows the roll angle maintaining itself

within $\sim\pm 6^\circ$, a significant improvement from the previous tests. The spikes at $\sim 15\text{sec}$ and $\sim 23\text{sec}$ show the system attempting to correct the large roll error, which works extremely well, preventing the boat from rolling any further. However, the response is quite significant, adjusting the roll by $\sim 10^\circ$ when these adjustments are made. While this system is working well to keep the roll within an acceptable range, the large adjustments shows that the system still requires further refinement. This will either come through a reduction in the parabolic proportional value, or a reduction in the in the order of the scaling function.

4.2 Altitude Control

4.2.1 Control Methodology

Though a standard PID loop could be used for the roll, the same implementation won't work for the altitude control. While the altitude can be controlled on its own through the ailerons, it is also important that its pitch is also kept at an acceptable level. To achieve this, a cascade PID loop was implemented, to allow both parameters to be adjusted together.

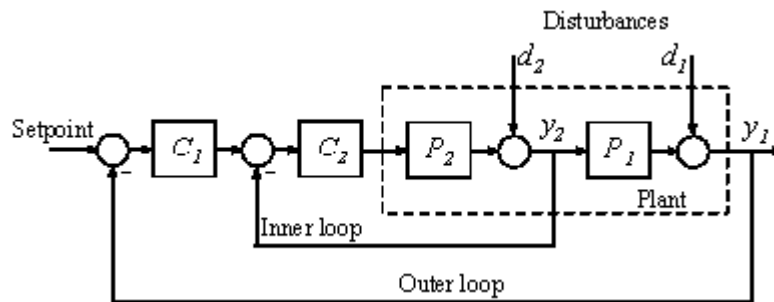


Figure 14: Diagram of a Cascade Control Loop [29]

By feeding the output of the altitude PID to the input of the pitch PID, the boats pitch can be controlled relative to the altitude, pitching it up if it's too low or down if it's too high. Then, once the altitude reaches the correct value the target pitch will then be set to $\sim 0^\circ$, adjusting to maintain a level orientation during travel.

4.2.2 Additional Hardware

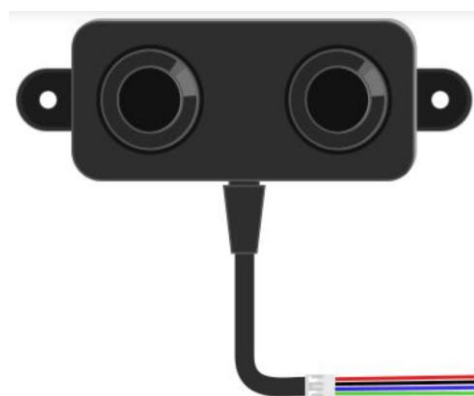


Figure 15: Front view of A02YYUW Ultrasonic Sensor [30]

Since it was discovered that the IMU may have issues calibrating while in the water, an additional sensor was required to measure the height of the boat. This was done through the use of an ultrasonic sensor, the A02YYUW shown in figure 15. This has several features making it optimal for this task,

including its minimum measuring distance of 3cm, 1cm accuracy, and 1mm resolution [31]. Additionally, it is designed to be waterproof, thus does not require extra modification to prevent it from damage.

4.2.3 Software

Software implementations for altitude control were similar to the required roll control software. Like roll control, fully manual testing was done initially which proved to be unfeasible for human control, thus the PID loops for altitude control were implemented shortly after. The PID implementations were done with the same struct and function method as done with the roll control; however, since this system is a cascade control loop the output of the altitude calculation is used as the set point of the pitch calculation.

Corrections were also made to the height readings obtained from the ultrasonic sensor; since the sensor is at the front of the boat, altitude and pitch readings may not adjust the boat as expected. Should the reading be the height at the front of the boat, if the altitude is at the target but the boat is still pitching upwards, the boat will attempt to correct itself by pitching down. This will then result in an incorrect altitude reading, requiring additional adjustments to get the altitude back to the correct point. By adjusting the measurement to give the height at the ailerons, when the correct height is reached, any pitch adjustments will pivot around the ailerons, resulting in the altitude remaining stable.

4.3.4 Results

Since this system contains two PID loops cascaded together, the tuning process becomes more complex. Ensuring both loops can achieve their desired control will first require the inner loop (pitch) to be properly tuned, since altitude is reliant on it.

Pitch:

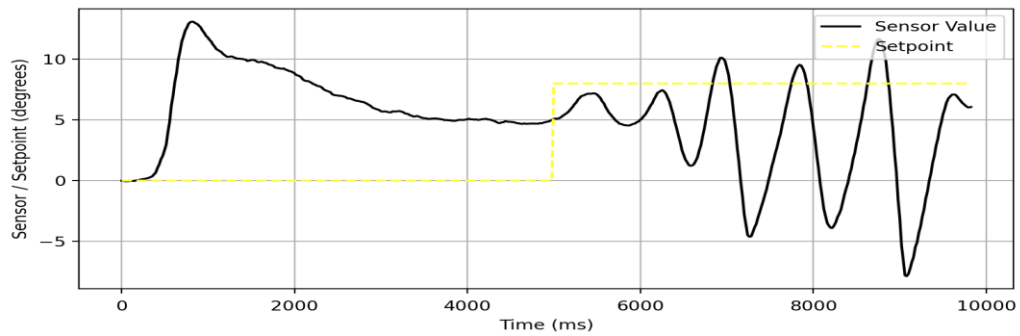


Figure 16: Pitch response at $P = 2200$

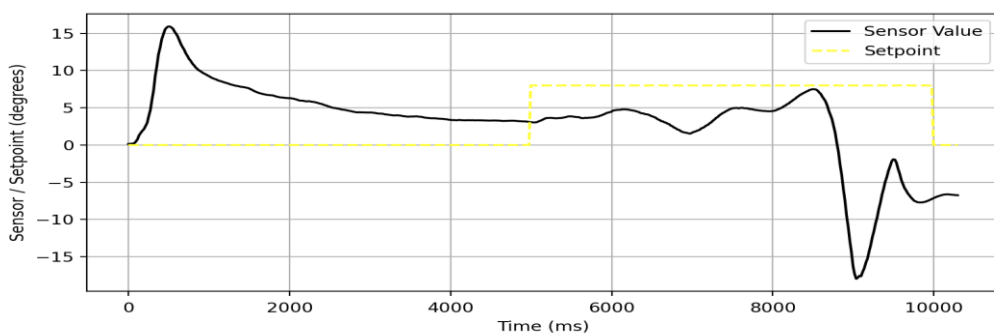


Figure 17: Pitch Response at $P = 1000$

These initial tests focused on tuning the pitch response to an acceptable level before implementing altitude control. It should be noted that testing the pitch control still requires the hull to be in a foiling state. As such, the altitude control was set up to contain a very small P value in order to allow feedback to give reasonable magnitudes for the pitch input.

The results shown above are from two initial tests, which contained only a proportion component. These show the P value's effect on the system, with the larger value causing severe oscillations and the smaller being unable to reach the target value. This was to be expected as this is standard response from a proportional controller [32]. However, regardless of the P value used, the tests all had the common flaw of having a large steady-state error. In order to counteract this, additional tests were performed with an added integral component, as well as the introduction of the derivative component to help counteract the unsteady output.

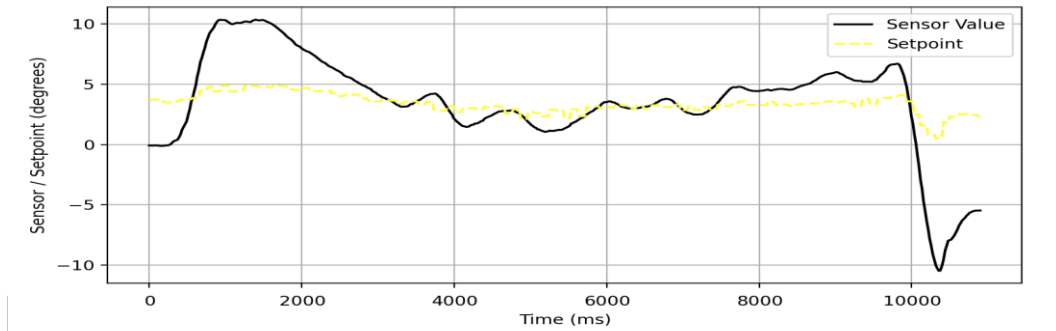


Figure 18: Pitch Response with $P = 1000$, $I = 100$, $D = 100$

With some adjustments to the PID parameters, the boat was able to achieve the response shown in figure 18, which shows a significant improvement. The integral component made significant improvement to remove the steady-state error, and the derivative component prevented large oscillations well. The response was still slightly unsteady, so required further tuning to address this, which was done through further adjustments to the P and D values.

This is also where the integral clamp was introduced. This clamp was introduced to limit the maximum value added to the integral each cycle as a means of preventing large changes due to prolonged error in the system. Since proper tuning of the controller should not result in large error there is minimal impact on the transient control. However, it does reduce the impact of the large pitch spikes caused by the initial acceleration. This feature does **not** limit the maximum value of the total integral.

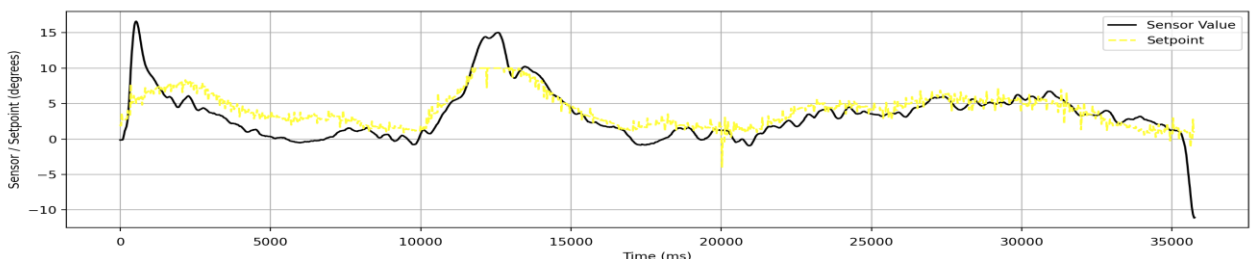


Figure 19: Pitch Response at $P = 700$, $I = 100$, $D = 200$

The final adjustments made to the pitch response are shown in the figure 19. The adjustments made showed significant improvement to the accuracy of the pitch response, being able to follow the setpoint with relative accuracy. This level of control was deemed accurate enough to meet the

requirement of the cascade controller; thus, these parameters were used for the remainder of the altitude tuning process.

Altitude:

During the tuning of the pitch loop, the altitude controller used a constant P value of 0.0004. These tests showed incapable of maintaining or even reaching the given setpoint, which provided an idea of where to start the tuning process. Initial tests thus focused on increasing the response magnitude of the loop, which required adjustments to the proportional and integral components. These adjustments can be seen in figure 20, showing multiple features that required further tuning.

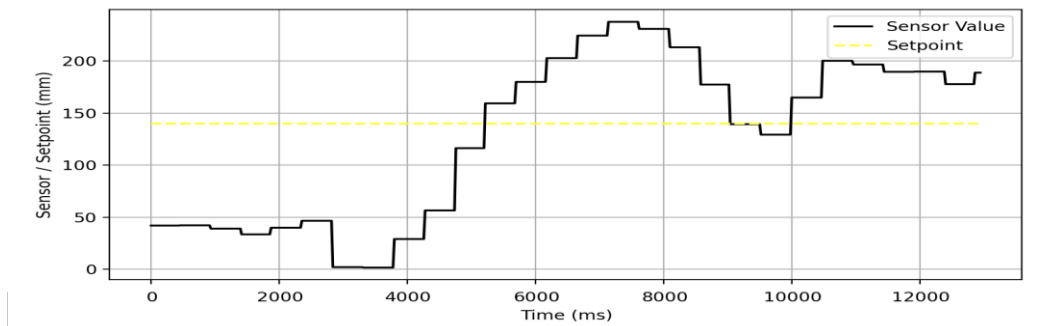


Figure 20: Altitude Control with $P = 0.0005$, $I = 0.0002$

The first issue with this response was the significant overshoot. This was a result of both changes applied to the control system and needed further tuning to prevent the boat from potentially breaching the surface of the water. The second major issue was the system's slow response time, which can be seen by the continued altitude increase after reaching the setpoint. This could be caused by two things: either the slow update time of the ultrasonic sensor, or an over-tuned PI value.

Further testing continued after updates to the hardware and software were implemented. These updates include parabolic scaling, increased ultrasonic sensor update rate, and increased altitude setpoint. Since there were several updates made to the whole system, tuning began again from a proportional controller. After some trial and error, the system landed on the below response.

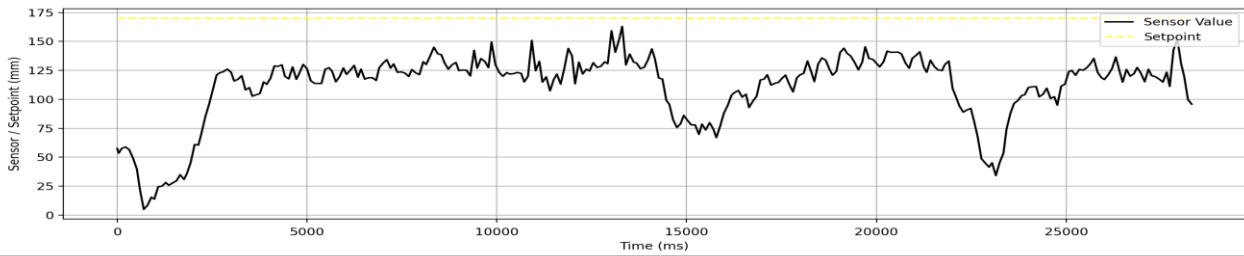


Figure 21: Altitude Control at $P = 0.001$ with Additional Parabolic Response

This implementation used only a proportional controller with an additional parabolic response. This system did an excellent job at maintaining a relatively stable altitude, with only minor changes required to smooth the response and eliminate the steady-state error. While there were dips at ~ 15 sec and ~ 23 sec, these were the result of the sudden adjustments made to the roll from figure 12.

Final Test:

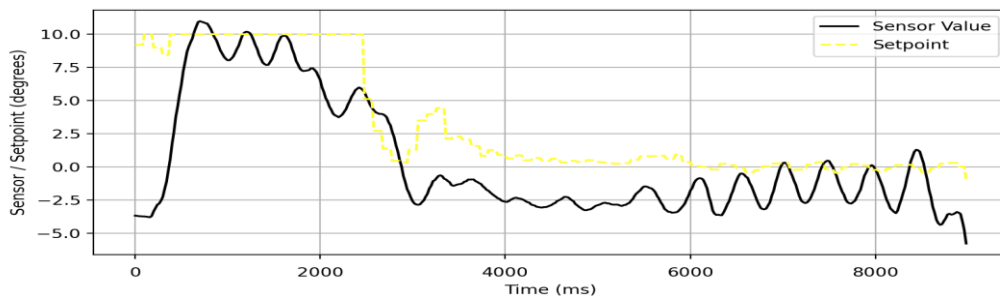


Figure 22: Pitch Response from Final Testing

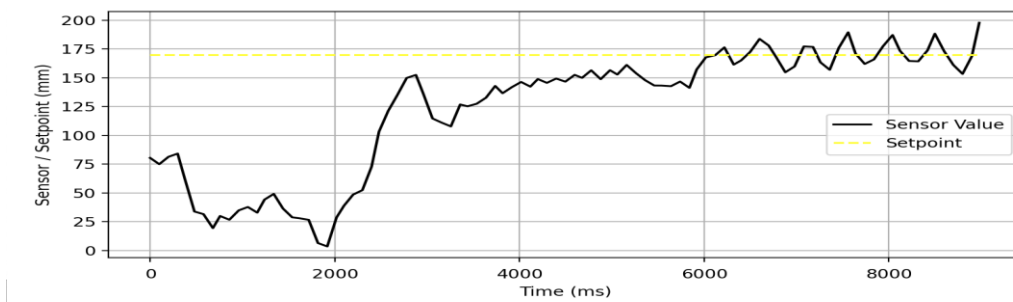


Figure 23: Altitude Response from Final Testing

These two figures show the responses from one of the final tests performed and show where they still require further tuning. The final pitch controller still requires adjustments, likely to all parameters, since there are still large oscillations and steady-state error. The altitude controller, however, reaches the set-point thus will only require minor adjustments to achieve near-perfect control. Despite these

inaccuracies, however, the implemented control systems function with enough accuracy to be able to achieve and maintain a foiling state for an extended steering test.

4.3 Autonomous Steering

4.3.1 Control Methodology

Autonomous steering was also implemented through the use of a PID loop. This method is the same as the roll control PID implementation; but instead uses the boat's current and target positions to generate a target heading, then compares it to the current heading to adjust the rudder and steer the boat. Though these additional calculations add a small amount of complexity, the overarching implementation of the control system itself is still the same.

4.3.2 Additional Hardware

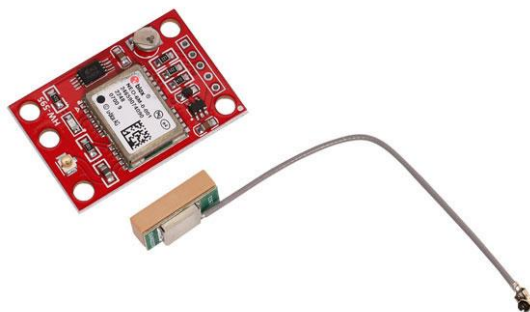


Figure 24: Picture of Neo-6M GPS Breakout Module and Antenna [33]

Since the Adafruit BNO085 was no longer being used, a different device was required to measure the boats heading and coordinate values. To achieve this, a Global Positioning System (GPS) sensor was integrated into the existing hardware. The chosen Neo-6M GPS has several features to make it a good fit for the current implementation. It uses UART by default but has the ability to implement I2C communication protocols if no additional GPIO pins were available. Its small size allows it to be installed alongside the other electronics without having to rearrange them; and it comes with an antenna to amplify signal strength. Its greatest feature, however, is its NMEA output.

4.3.3 Software

In order to utilise the GPS module, the output data must be parsed so the individual components can be used as needed. The only downside to this is that the NMEA format uses an ASCII output and multiple sentence formats [34]. Coding this by hand would be tedious, timely, and leave much room for error. Fortunately, code libraries already exist to perform this operation automatically. The TinyGPSPlus library is one of these, and automatically processes the data fed into it. This then outputs coordinates and headings, as well as having in-built heading calculations functions, further reducing the work required to implement GPS tracking.

There is a minor flaw with this GPS implementation, however. The selected Neo-6M has a base update rate of 1Hz, which is comparatively slow to the loop frequency of 50 Hz. However, this should not be a major concern as these inputs should update the yaw target value and steer the boat towards it until the next one is received. Slow GPS updates may cause incorrect steering if the boat is not travelling towards the target point while close to it; however, once the boat is within a certain range of the target position it should be considered to have arrived at this destination, and either stop or begin steering to the next waypoint.

4.3.4 Result

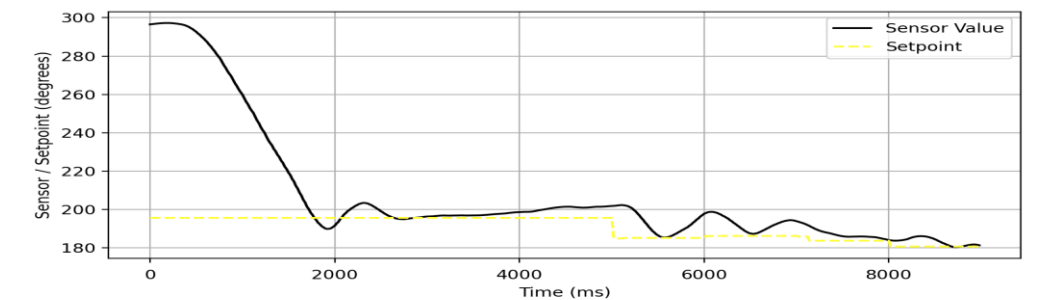


Figure 25: Yaw Control Response at P = 720

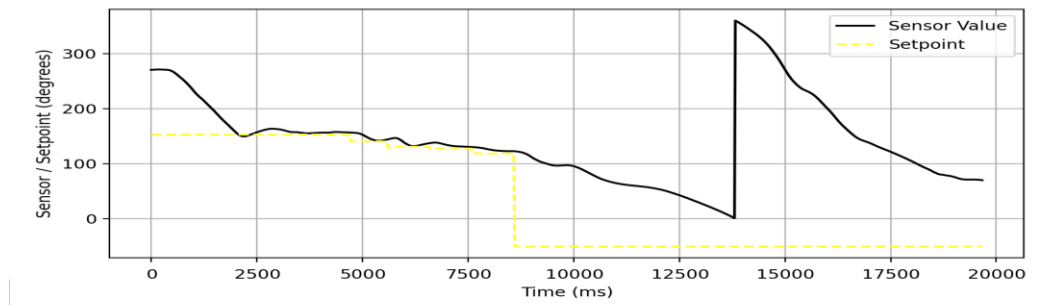


Figure 26: Yaw Control Response at P = 720

Due to time constraints, there was limited ability to implement, test, and tune autonomous steering systems. Figures 25 and 26 above show its final implementation.

Since time was limited, the control system was only tuned enough to implement autonomous steering, which resulted in a basic proportional controller. The more important feature of this system is the ability to track coordinates and headings to ensure these can be fed into the control system. While the movement is oscillatory due to the proportional controller, figure 25 shows this system being able to correct itself by 100° to steer towards the target and then continue to adjust as the setpoint updates.

Figure _bottom_, however, shows the predominant issue with this feature's implementation. Since there is rollover from 0° to 360° and vice versa, steering across this border requires a more complex implementation. This causes problems with error calculations, as it works through the same implementation as the roll control, which results in the controller steering the vessel the wrong way. This idea can be seen in figure 27 below.

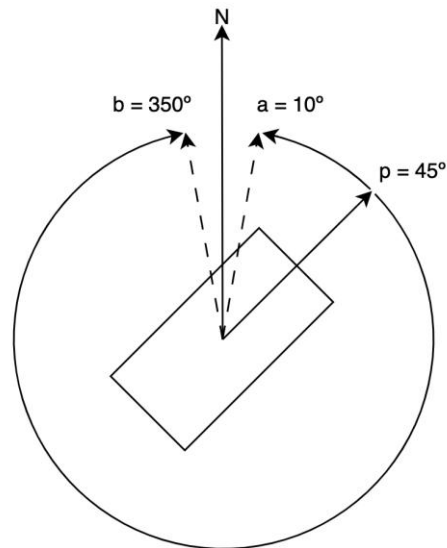


Figure 27: Example Yaw Error Calculation

Here, the error between setpoint 'a' and current value 'p' is -35° , which will result in it turning anticlockwise in order to reach it. However, this same error calculation gives an error of 305° for setpoint 'b'. Despite setpoint 'b' being -55° from the current value, the positive error from the calculation causes it to turn clockwise 305° instead of the simpler -55° . Corrections for this were implemented, however, the test in figure 26 shows the setpoint becoming negative and failing to update further, thus requiring further refinement to ensure correct implementation.

Despite the failure to properly implement this feature, figure 25 still provides a successful proof of concept. Since the limitations come from implementation errors, rather than the inability of the system itself, fixing these issues should allow for the implementation of fully autonomous steering.

4.4 Future Improvements: Active Roll Control

As shown above the current system still has improvements to be made before it can be considered viable. The goal of being able to implement active hydrofoils is that since they don't self-stabilize, the vessel should be able to control them so it can bank and take sharper turns. However, there are several issues in addition to the PID tuning that need to be addressed before this can be implemented. The current implementation for each control loop maps the input angle or distance to a PWM signal through the PID system(s) and uses this to directly adjust the ailerons. This is a crude method that leaves room for error due to non-linear mappings, particularly from PWM to aileron angle.

The way to improve this would be to treat the output of the PID loop as a force. By treating the output this way, the required angle can then be calculated taking into account additional variables that could not be in the current implementation, such as its speed. Once the aileron angle has been calculated, a mapping function can then be used to convert this directly to the required PWM signal. This implementation would require the vessel to be able to track its speed; however, both the GPS and IMU are capable of implementing this, thus additional hardware should not be required.

By improving the design of the control system, it can then be used to implement banking through a more practical means. The current implementation focused purely on keeping the vessel upright; however, this is impractical as performing turns introduces centripetal force [35]. Rather than attempting to correct the roll during these turns, the implementation of banking would allow it to angle towards them, preventing rolling pre-emptively and allowing the boat to take sharper turns.

5. Conclusion

With the goal to develop a vessel that can achieve and maintain a foiling state with autonomous steering, this project has been mostly successful.

The implemented control systems show great ability during testing, but it is clear that further tuning is still required in these areas. These systems have successfully maintained the vessel's balance and height allowing for semi-autonomous steering to be implemented, though still require additional tuning to refine the transient response. Despite this, however, their current states have been developed to a level capable of achieving and maintaining a foiling state, showing the feasibility of active hydrofoil implementations.

While it was planned, autonomous steering was not fully implemented. Due to issues developing the algorithms required to achieve it, certain cases result in the vessel getting stuck in a loop. However, the capability for autonomous steering is present, and only requiring slight adjustments to achieve. Further steps for future development would be to modify the control systems to make the implementation of banking feasible, which would make turning more effective and assist in further control of the boat's roll.

This project has shown significant improvements in the development of active hydrofoil systems. While issues are still present, there is clear direction on how to continue fixing and improving on the available design. At the current rate, these developments could be implemented in a full design in the near future, helping to lead to a greener future.

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Appendix A (Literature Review)

The concept and use of hydrofoils have been around for over 100 years and have been used to improve the efficiency at which boats operate, and the speed at which they're able to travel [36]. Since then, hydrofoils have improved significantly with different profiles and submerging methods allowing for a variety of optimisations to be made [37][38]. However, there are still issues that remain in their current state, most notably, the lack of manoeuvrability and/or stability [6]. Due to their instability, fully-submerged hydrofoils are often overlooked in favour of the more stable, surface-piercing (passive) hydrofoils. While these work for their goal of boosting speed and efficiency, they do so by sacrificing manoeuvrability due to their static nature.

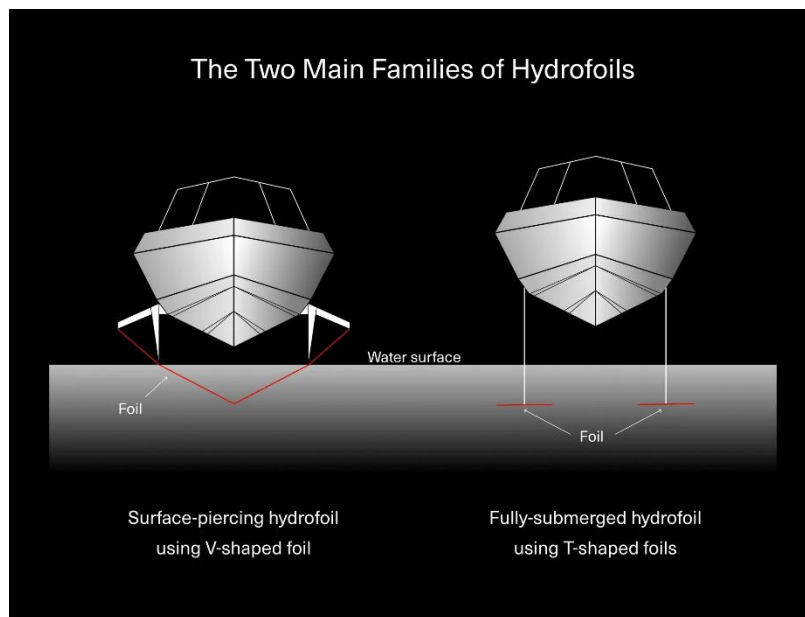


Figure 28: Surface-piercing vs Fully submerged Hydrofoils [6]

Hydrofoils themselves are a wing-like attachment placed on the bottom of boats in order to generate lift, and by attaching them to a mast, they can then remain submerged after the hull has risen out of the water [39]. Similar to how plane wings work, hydrofoils use fluid flow to create a pressure difference across it, resulting in a lift force [40]. By increasing speed, the lift force can be increased until it is large enough to counteract the weight of the boat, lifting it out of the water. Since this rise completely removes the hull's contact with the water, there is significantly less drag due to friction which increases the boats efficiency and potential top speed.

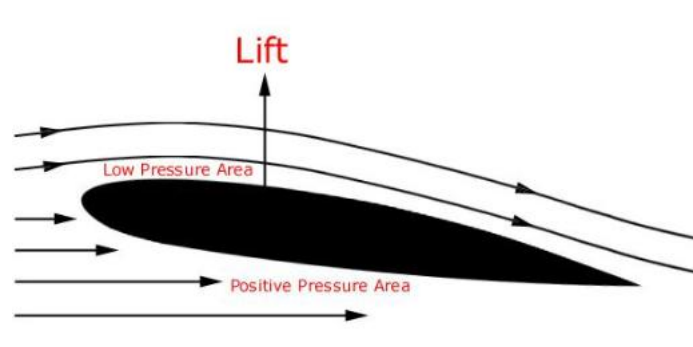


Figure 29: Working Principles of Hydrofoils [41]

While they tend to struggle in boating applications due to their instability, fully-submerged hydrofoils have been used in foilboards for many years [42]. By attaching a fully-submerged hydrofoil to a surfboard, they too can obtain the benefits offered by hydrofoils. However, the key that allows a foilboard to work over a boat, is their capability for oscillation and the fact that the user acts as the active stabiliser. By shifting their weight, the board can be tilted altering roll, pitch, and this lift, according to the user's movements.

Since a boat's weight cannot be shifted in the same way, this method cannot be used to achieve the required control, so modern research must look towards active (controllable) hydrofoil systems to achieve the same benefits. By allowing the hydrofoils to pivot, an active stabilisation system can be implemented and the disadvantages of fully-submerged hydrofoils can be negated, additionally resulting in added disturbance rejection [6]. This regains manoeuvrability while maintaining the other improvements offered by hydrofoils; however, stabilisation is not a simple task. Due to their construction, fully-submerged hydrofoils lack the ability to create any horizontal forces that may stabilise the boat's roll. Therefore, roll control must come through separate aileron adjustments, in order to create a difference in the lift applied to either side [6]. This same mechanism can then be used to bank the boat, allowing for increased manoeuvrability lacked by passive foils.

In order to stabilise the boat, control systems must be effectively implemented and fed data. This requires hardware and software to determine the boat's state, adjust outputs, and handle intermediate tasks including the control system. Different types of control systems such as Performance, Integral and Derivative (PID) controllers, linear controllers, and fuzzy controllers can be compared to

determine the advantages, disadvantages and performance capabilities of each. Additionally, disturbance rejection is important to reduce the effects on the boat by waves, which can be done through a feed forward controller to further increase the already impressive abilities of active hydrofoils.

Appendix B (Final Hull Design)



Figure 30: Top view of final hull



Figure 31: Side-front view of final hull on a support stand