UNIVERSITY OF WESTERN AUSTRALIA

HONOURS THESIS

# Developing an Autonomous Hydrofoil with Waypoint Driving

*Tiziano Wehrli*

School of Engineering

Supervised by

Prof. Dr. Thomas Bräunl
Kieran Quirke-Brown

14 October 2024

Word Count: 7998

# Abstract

The objective of this project was to build a one-metre-long, autonomous electric hydrofoil that would be capable of rising up onto foils and autonomously driving to GPS waypoints. Due to the demanding nature of the project, this paper focuses on the hull design and construction, roll control and autonomous heading following.

The first reason for undertaking this project is to develop a user-friendly test platform for UWA to explore innovative hydrofoil technology, such as different wing designs, configurations and control mechanisms. The hydrofoil will also be used to advance the under-explored area of autonomous hydrofoil driving in literature.

The hull and hydrofoils were designed and built from scratch, using a combination of laser cut wood and 3D printed PLA parts. Accessible, "off the shelf" electronics were used to control the boat and implement autonomous driving. A microcontroller was used to implement control algorithms, which stabilise the hydrofoil boat and act as a flight controller. An inertial measurement unit (IMU) paired with a global positioning device (GPS) was used to implement straight-line waypoint driving.

The overall outcome of the project was a fully constructed hydrofoil boat with partial control and autonomous driving implemented. The construction of the hull and hydrofoils was successful, along with the integration of electronics and software. As such, the boat can be driven using a remote control and can rise out of the water using the hydrofoils. However, the control algorithms are unable to keep the craft stable due to limitations in the aileron design, and so the boat is unable to foil continuously and will fall back into the water. The autonomous driving has been implemented, but due to these limitations, it operates when the boat is not foilborne.

The primary focus of future work should be to fix the limitations with the ailerons, allowing them to provide proper control and stability of the hydrofoil boat. The brushless motor providing propulsion should also be replaced with a motor of the correct specifications to prevent the existing overheating issue.

## Acknowledgements

I would like to extend my gratitude towards my colleague Agnibho Gangopadhyay, who worked on this project alongside me. His support, time and effort are reflected in the progress we made as a team.

I would also like to thank Pierre Louis-Constant for finding time to help us and share his expertise on marine engineering and hydrofoils.

I would like to extend a large thank you to my supervisor, Professor Thomas Bräunl, for his support and guidance throughout this project and for providing us with an opportunity to explore such an interesting topic. I would also like to thank his PhD student, Kieran Quirke-Brown for his guidance and supervision in Professor Bräunl's absence.

Finally, I would like to extend my gratitude towards my family, who gave me their never-ending support and encouraged me to persevere and press on despite the difficulties and setbacks we encountered in this project.

# Contents

# 1 Introduction

It is well known that the usage of fossil fuels and climate change present a large issue in modern-day society [1]–[3]. Several international sustainability organisations and the literature agree that the consumption of fossil fuels is unsustainable, and has a large negative impact on the environment. They also agree that in order to minimise these impacts, it is necessary for society to transition towards sustainable fuels, vehicles and net zero emissions [4]–[6].

| Type | Years | Measure | Target | Current status |
|---|---|---|---|---|
| Short-term | 2018-2023 | New Energy Efficiency Design Index (EEDI) phases | New vessels | -10% in 2015<br>-20% in 2020<br>-30% in 2025 |
| | | Operational efficiency measures (e.g. SEEMP, operational efficiency standard) | In-service vessels | SEEMP planning required |
| | | Existing fleet improvement program | In-service vessels | – |
| | | Speed reduction | In-service vessels | – |
| | | Measures to address methane and VOC emissions | Engines and fugitive emissions | – |
| Mid-term | 2023-2030 | Alternative low-carbon and zero-carbon fuels implementation program | Fuels/new and in-service vessels | – |
| | | Further operational efficiency measures (e.g. SEEMP, operational efficiency standard) | In-service vessels | SEEMP planning required |
| | | Market-based Measures (MBMs) | In-service vessels/fuels | – |
| Long-term | 2030+ | Development and provision of zero-carbon or fossil-free fuels | Fuels/new and in-service vessels | – |

Figure 1: International Maritime Organisation strategy. [7]

These changes have also been brought into the marine industry, with the International Maritime Organisation (IMO) decreeing that strategies are required to reduce the carbon consumption of marine vessels [7]. The specific IMO goals are illustrated in Figure 1.

Without new sustainable developments, the marine industry will lag behind the sustainability agreements of the future.

As such, attention has turned towards hydrofoil boats, which offer significant advantages in terms of efficiency (and thus sustainability) compared to regular boats. This is because hydrofoil boats lift the hull out of the water, reducing the vessel's drag during operation. The Swedish company Candela is pioneering electric hydrofoil boats and has proved that hydrofoil boats are more efficient with their first boat, the C7. Candela has experimentally determined that the C7 requires 0.8 kWh per nautical mile, and uses the same power when travelling at 5 knots with the hull in the water as when travelling at 22 knots with the hull out of the water [8]. The C7 is also 80% more efficient than conventional diesel boats [9].

Figure 2: Wake comparison of the Candela C7 and a monohull. [8]

Hydrofoils also offer other improvements compared to regular boats. As the hull does not cut through the water, they produce almost no wake. This is demonstrated in Figure 2, with the C7 on the left producing significantly less wake compared to a conventional boat on the right. This reduces the impact on other water users and the environment [10], [11]. Hydrofoils also possess superior seafaring capabilities in open seas. A hydrofoil boat with a well designed control algorithm is able to reject wave disturbances and maintain a constant orientation. This means it does not sway in waves like a conventional hull does, which significantly improves comfort. It also increases their accessibility by allowing individuals who suffer from sea sickness to utilise them [12].

The United Nations has identified a shortage of skilled maritime workers [13]. Autonomous hydrofoil technology can be used to fill this gap, reducing the size of the required crew. The development of simple way point driving in hydrofoil boats is the starting point for autonomous driving in this type of craft. Research can then expand on this area, allowing the development of fully autonomous hydrofoils.

These issues in modern-day society have shaped the goals of this project, which is to advance hydrofoil technology by developing a small, autonomous electric hydrofoil. This will improve the sustainability and environmental friendliness of the boating industry and expand the research on autonomous hydrofoils to alleviate the shortage of skilled maritime workers.

# 2 Literature Review

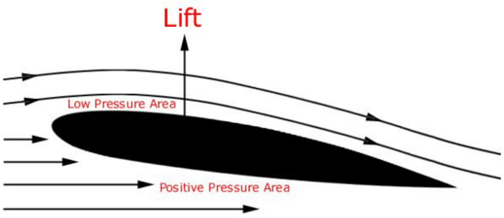


Figure 3: A hydrofoil wing. [14]


Figure 4: Boeing 929 Jetfoil. [15]

The term "hydrofoil" is often used interchangeably with "hydrofoil boat", though a review of the literature and online resources demonstrates that the hydrofoils are the wings of the craft. A hydrofoil is a wing-like structure that generates lift in water, which is demonstrated in Figure 3. A hydrofoil boat is shown in Figure 4, and it is an ordinary hull with hydrofoils mounted underneath it on long masts. As the boat's velocity increases, the hydrofoils produce more lift, eventually pushing the hull entirely out of the water. In this foilborne state, drag and the impact of waves on the hull are significantly reduced [16]. This report and project focuses on submerged hydrofoil boats, which feature horizontal hydrofoils that remain submerged during operation. Once foilborne, these crafts are inherently unstable and require control surfaces paired with control algorithms to keep them at a constant height and orientation [12].

The current state of the art and modern-day hydrofoil boat innovation are based around submerged hydrofoils. Despite being more complicated and expensive to develop and manufacture, these crafts provide far superior seafaring performance and comfort due to their disturbance rejection.


Figure 5: The Candela C-7. [8]

As society aims to become greener and more sustainable, significant research and development has been conducted by corporations on developing electric hydrofoil boats. This includes Candela's C7 (shown in Figure 5), BMW's "THE ICON" and Artemis' eFoiler [17]–[19]. These corporations have made significant advancements in this area, having solved the complicated problem of keeping the foilborne boat stable and implementing robust disturbance rejection. Unfortunately, these companies do not publicly release the details behind their work, preventing it from contributing to the literature. As such, there is a large gap in the literature in terms of the holistic approach behind designing and building a hydrofoil from scratch. Numerous publications have been produced on the individual aspects and components of hydrofoil boats, but these do not present an insight as to how all the components and aspects link together.

The hardware aspect of solving the hydrofoil control problem is to establish the control surfaces that will be used. That is, what hardware the craft will utilise to change its orientation once it is foilborne. There are several different ways to do this, including trailing edge flaps, ailerons or variable incident foils [12]. The literature does not explore different hardware methodologies in depth, and so careful consideration and selection of the control surface is required based on the requirements and constraints.

The other aspect of the hydrofoil control problem is the control loop and software used. This consists of selecting sensors to measure the boat's state and then passing this data into control software to adjust the control surfaces, ensuring the boat remains stable. A reliable approach to measure the boat's height above the water is to use an ultrasonic ranging device, which is preferred over other sensors due to simplicity, cost and performance [20]. Proportional, integral and derivative (PID), linear quadratic regulator (LQR) and sliding mode control have been compared to determine which performs better in waves, allowing a comprehensive definition of the benefits and disadvantages for each control loop type [21]. In addition to this, a fuzzy controller can be used to improve upon the disadvantages of LQR (poor performance when it is far from the operating point) and offer effective control [22], [23]. Another aspect of the control algorithm is to introduce disturbance rejection to improve the stability of the craft in waves. One method to do this is to use an extended disturbance observer [24]. Overall, the control theory of the hydrofoil craft is broad and well-researched, which will be leveraged to select the optimal control loop for this project.

Advancements have been made in current literature regarding autonomous boat technologies. The literature has focused on a variety of aspects, exploring different control hardware and driving software for autonomous boats. This includes the development of an autonomous electric catamaran using ArduPilot [25], a small-scale autonomous boat to test course-keeping manoeuvres [26] and autonomous sailboats [27]. Software developments have also been made in the literature, including autonomous driving using an inertial measurement unit (IMU), global positioning system (GPS) and compass integration [28], autonomous driving using artificial neural networks [29] and autonomous driving to control an autonomous surface vehicle (ASV) using a PID loop [30]. However, the research in regard to autonomous and unmanned hydrofoils is fairly limited. Hydrofoils add an additional layer of complexity to autonomous driving as the software needs to lean the boat to the correct angle when turning. The software also needs to handle acceleration of the boat and attitude control to ensure the boat rises onto the foils smoothly. Some advancements have been made in developing the roll dynamics and correct lean angles for turning hydrofoil boats, with a Robust Integral of the Sign of the Error (RISE) feedback strategy successfully used to control the roll orientation of the boat to perform a curved turn [31]. However, the literature remains fairly limited in regard to the exploration of autonomous hydrofoils. There is little information on autonomous GPS waypoint driving, decision-making capabilities and collision avoidance specifically for hydrofoils. Furthermore, the literature has not analysed how autonomous driving in regular boats can be scaled and adapted to be used in hydrofoil boats.

The literature for the submerged hydrofoil craft is more developed in the aspects of stability and control theory of the craft. However, the other aspects remain fairly limited. The current literature does not present an in-depth assessment of the different control hardware that can be used and the advantages and disadvantages of each type. The development of autonomous hydrofoils is quite unexplored, especially in terms of advanced autonomous driving and unmanned missions in the open sea. Furthermore, the narrow focuses of the individual research papers result in a lack of information regarding how the different hydrofoil craft aspects can be combined to develop a well-engineered and robust hydrofoil craft. The industry has been successful in this area, but the hidden nature of such developments results in a gap in the literature.

# 3 Project Objectives

## 3.1 Overall Aims

The objective of this project is to develop a small-scale, electric autonomous hydrofoil. This hydrofoil boat will be approximately 1 metre long and will be capable of rising out of the water using hydrofoils. It will be able to turn autonomously, control its velocity and traverse GPS waypoints while maintaining a stable orientation and altitude.

The autonomous driving aspect of this boat is one of the key benefits and reasons for undertaking this project. While this is a rudimentary form of autonomous driving, it will provide a proof of concept for basic autonomous hydrofoils. It is also a starting point in the literature for the development of autonomous hydrofoil driving. The finished product can then be utilised by future University of Western Australia (UWA) students and academics to develop more advanced autonomous driving algorithms for hydrofoil boats. As such, this provides a platform to expand the literature in autonomous hydrofoil driving.

The other key benefit of this project is that it will provide UWA with an easy-to-use test bed that can be used to develop different hydrofoil hardware, software and control technologies. This can then be scaled and deployed to larger and more complicated hydrofoil boats. The small and simple design of this hydrofoil craft results in much easier modification and testing compared to larger watercraft. Undertaking this project will also increase the hydrofoil knowledge and experience within UWA. While the development and construction of this hydrofoil craft will not directly contribute to the literature, it provides the groundwork for more advanced control software and hardware testing in the future.

## 3.2 Report Aims

This project was undertaken by two students due to its demanding nature. As such, this report will focus on certain subsections of the overall project, specifically:

### 3.2.1 Hull Design and Construction

This objective encompasses the tasks involved with the hull, which include designing the hull and fabricating it. In contrast, the other report will focus on the wing design and construction.

### 3.2.2 Roll Control Development

This report will focus on the roll control aspect, which is maintaining stability in the roll direction (preventing the hull from tipping over sideways). The other report will focus on the pitch (altitude) control.

### 3.2.3 Development of Autonomous Heading Following

Due to the demanding nature of this project, autonomous driving will only be implemented as a simple GPS waypoint driving algorithm. This will drive the boat in a straight line between GPS waypoints. One aspect of achieving this is to have the boat follow a constant compass heading in a straight line, which will be the focus of this report. The other report will cover calculating the desired heading based on the desired GPS location and the boat's current GPS location.

It should be noted that this report will not cover any design, construction or implementation details outside of its scope, unless the information is required for context.

# 4 Design Process

## 4.1 Hull Design

### 4.1.1 Constraints and requirements

The constraints and requirements are a critical starting point, as this is the selection criteria that will be used to decide on the final design.

The fairly limited budget was the biggest constraint for this project. As such, it was important that the hull construction was as cheap as possible to ensure that there was sufficient remaining budget for other aspects. The overall budget for the project was $1000.00 AUD, of which it was expected that around $200-$300 would be a reasonable allocation for the hull. It is critical that the hull still meets the other requirements, which is why the hull was designed with the mentality of being as cheap as possible while still meeting those other constraints.

The size of the hull and wings were carefully chosen before commencing the design phase of the project. This requires balancing requirements, as a smaller hull is easier to use for testing but appears less impressive and is harder to build. A length of 1 metre was chosen, as this is still small enough to provide simple transportation but large enough to appear physically impressive in demonstrations and presentations. Furthermore, the task of miniaturising things can be quite complicated, as small hulls and wings require tighter tolerances when manufacturing and have less room to fit electronics inside of them. The 1 metre length was considered large enough to ensure ease of manufacturing and sufficient space for components.

The last requirement/criteria was in relation to the aesthetics of the hull. As this is a hydrofoil boat, the shape of the hull is not as relevant as with conventional boats. This is because the hull is above the surface of the water, so it does not require low hydrodynamic drag. Because of this, the simplest, fastest and cheapest hull solution is to purchase a 1 metre long box. However, this would have caused the hull to not resemble a boat and appear quite unaesthetic (which would also make it less impressive in demonstrations). As such, a key requirement is that the hull would need to look like an actual boat and have a boat-like shape.

### 4.1.2 Material Choice and Construction

These two concepts go hand in hand, as the material chosen for the project will affect the construction process. Several different methods were considered.

Figure 6: A pre-made, lightweight (1.00 kg) fibreglass hull. [32]

Buying a pre-made hull was considered, as it offers several advantages compared to building one from scratch. The biggest benefit is time, as building a hull is a fairly long process and buying a pre-made one would save a lot of time. Furthermore, this would have resulted in a much higher quality hull, as these manufacturing companies have far superior expertise in hull construction and access to more advanced machinery. However, the largest drawback is that 1 metre long hulls are quite expensive to buy, as they typically have a more complicated shape and are made from fibreglass or some similar expensive and lightweight material. This is because these hulls are built to be used for model racing, which increases cost as they need to perform at a high level.

The two main ways to build a model boat from scratch are to either cut wooden panels from sheets and glue them together or to use a mould to cast a fibreglass hull.

The advantage of building a hull out of wooden panels is that the construction process is much simpler and faster than casting fibreglass. A laser cutter can be used to quickly cut the panels out of wooden sheets. These panels can be glued together using wood glue to form a hull. Once this has been done, the hull just needs to be coated in resin to waterproof the wood and adhesive. However, the disadvantage of this construction method and material is that the final hull is much heavier compared to a fibreglass hull. This is because fibreglass is a lot stronger than wood, so thicker sheets of wood (3mm-6mm) are required to ensure the hull is structurally sound. Even then, the hull is not as strong as fibreglass, leading to a shorter lifespan and poorer impact resistance.

In comparison, the advantage of a fibreglass hull is that it is significantly lighter than wood, as the hull can be made from much thinner sheets. This material is also significantly stronger than wood, so the hull is highly impact resistant and will possess a longer lifespan. The drawback of a fibreglass hull is the construction procedure, which is more complicated, expensive and requires more time. This is because the mould needs to be built from wood first, and then coated. After this, the mould can be lined with fibreglass and resin applied to harden the fibreglass. The pieces then need to be removed, sanded and joined together.

### 4.1.3 Design Software

The design stage is an important part of a project, as developing a comprehensive and detailed design minimises the number of issues and oversights found during or after construction (which is often too late and creates additional complications). It was decided for this project that 3D computer-aided design (CAD) software would be used to create a full model of the entire boat (complete with the hull, electronics and wings) to ensure that all parts fit, worked properly together and that there were no oversights or poor design assumptions.

The software chosen to do this was Autodesk's Fusion360, as both students undertaking this project are familiar with it. This improved the design procedure as it allowed for a single collaborative document to be used. Furthermore, Fusion360 has several useful tools, such as finite element analysis (FEA) which was used to inspect the strength and structural integrity of the final hull design.

## 4.2 Roll Control

### 4.2.1 Constraints and requirements

Compared to the hull design, this task is more software and sensor based rather than design and construction based. As such, there were fewer constraints and requirements, and they were less involved in this aspect.

One of the requirements was that an Arduino-based microcontroller would be used, which means that the chosen sensors would have to be capable of communicating with it. Furthemore, the programming language would have to be C++, as this is what Arduino Integrated Development Environment (IDE) and compiler use and understand.

The only other main requirement was again budget. This was only really applicable to the sensors, so it was necessary to choose these with costs in mind.

### 4.2.2 Control Hardware

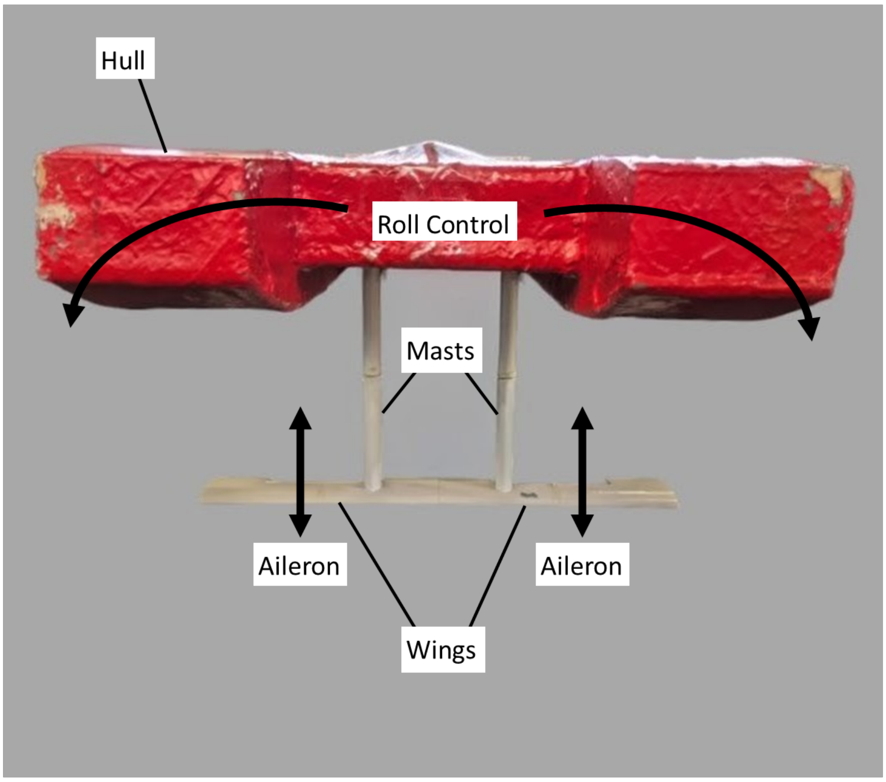


Figure 7: Final hydrofoil boat with ailerons used to control roll

This report does not focus on the control hardware, as this is not within the scope of this report (this would fall under the category of wing design and construction). However, for context, it should be noted that ailerons were the chosen control surface to use to adjust the boat's orientation once the hull is out of the water. The ailerons are permanently submerged, and by moving up or down, they can create upwards or downwards forces on either side of the hull centre. By moving the ailerons in opposite directions, a net moment can be projected onto the boat, allowing it to be rolled left or right. This is illustrated in Figure 7.

### 4.2.3 Control Methodology

It should be noted that a closed loop controller must be used here, as the microcontroller needs to know what the boat's orientation is to determine how to move the ailerons. It would not be possible to do this "blind" (without any sensor data).

As mentioned in the literature review, a variety of different control algorithms have been tested and are presented in the literature. These include PID, LQR and fuzzy controllers, with each presenting different advantages and disadvantages. The selection method here is to choose the simplest and fastest one to implement that still offers suitable performance. This is because the time allocated for this project is limited (given the large and challenging scope), and so the focus of the control aspect is on developing a simple and working control routine that can keep the craft stable, rather than developing the most robust and advanced control loop.

### 4.2.4 Sensor

As mentioned in the previous section, sensors are necessary to measure the boat's state at any point in time. This is used by the control loop to determine how to move the ailerons to ensure the boat's orientation remains at the desired value.

The most common way to measure orientation and pass it into a microcontroller is to use an inertial measurement unit (IMU). These devices can be purchased as a small chip, which is mounted on the hull and then plugged into the microcontroller to pass in its current orientation. These devices typically feature onboard sensor fusion, which combines accelerometer, gyrometer and magnetometer readings to directly provide accurate orientation angular data.

Other sensors were not considered for this aspect, as IMUs are widely used as the standard device to measure orientation and offer reliable and accurate performance.

## 4.3 Autonomous Heading Following

### 4.3.1 Constraints and requirements

In a similar manner to the roll control, this is not a design and construction based task and so does not have as influential constraints. This task itself is very similar to the roll control, except that it focuses on maintaining a constant yaw orientation rather than a constant roll orientation. The overall constraints are also very similar, with a focus on budget (minimising cost) and ensuring compatibility with an Arduino board, the Arduino IDE and the C++ programming environment.

### 4.3.2 Control Hardware


Figure 8: Final hydrofoil boat with a rudder used to control yaw

Once again, the control hardware will not be explained in detail as it is not within the scope of this report. However, it should be noted that the chosen method to change the yaw orientation is to use a rudder (just like with a regular boat). The rudder is mounted to the back of the boat, and turning it right or left will change the boat's heading. This is demonstrated in Figure 8.

### 4.3.3 Control Methodology

This is a very similar problem as the roll control, as it involves a closed loop controller with a sensor providing feedback and an output that adjusts the boat orientation. As such, the same controller will be used here as with the roll control, for the same reasons previously mentioned.

### 4.3.4 Sensor

The IMU used for the roll control will be re-used here. IMUs measure rotation in all three axes, roll, pitch and yaw. The yaw value presents the boat's current heading, which is used as feedback for the heading controller to calculate how to move the rudder. As IMUs are equipped with magnetometers, the yaw heading is already relative to true north, and so it directly provides the boat's compass heading. This value can then be used by the control algorithm to track a desired heading and drive autonomously between waypoints.

# 5 Final Design

## 5.1 Hull Design and Construction

### 5.1.1 Construction Methodology

The hull was constructed out of wooden sheets that were cut and glued together. Purchasing a pre-made hull was rejected due to the increased cost (over $250). Casting a fibreglass hull was also rejected due to limited experience in this area and the additional cost and time required.

Once all the wooden pieces were glued together, the boat was coated in resin and fibreglass to waterproof it and make it significantly stronger. This was done to significantly improve strength without the complexity of needing to cast fibreglass. However, this resulted in the hull being much heavier.

### 5.1.2 Hull Design

Once the construction process was chosen, it was possible to start designing and modelling the hull.

As the construction process was to glue sheets together, the simplest and strongest hull shape is a rectangular prism. The final hull design was a catamaran, as this maintains a box structure/shape while appearing much more boat-like.

The catamaran hull was constructed by producing three separate boxes (two pontoons and a main body) and then gluing them together. This design offers improved structural integrity compared to a monocoque and it doesn't require bulkheads for support.


Figure 9: Pro Boat RC racing catamaran. [33]

The dimensions and proportions of the hull were determined by using an existing model racing catamaran hull, shown in Figure 9. This was done purely for aesthetic reasons, as the drag produced by the hull in the water and hull planing speed are negligible.

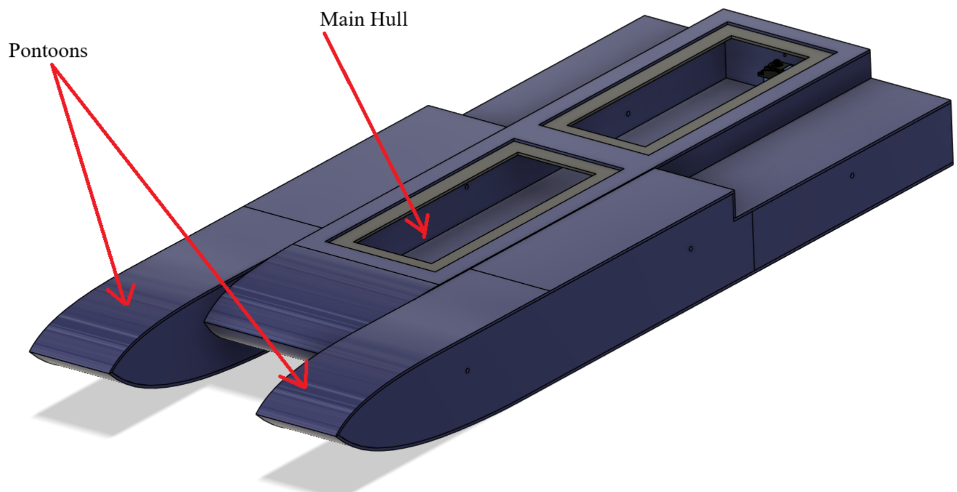


Figure 10: Hull design modelled in Fusion360

Figure 10 illustrates the final design. The hull was designed in three separate pieces, with two pontoons on either side of the main body. The main body has two openings on the roof, which will allow all of the electronics to be mounted inside. These hatches are sealed during operation to ensure they are watertight.

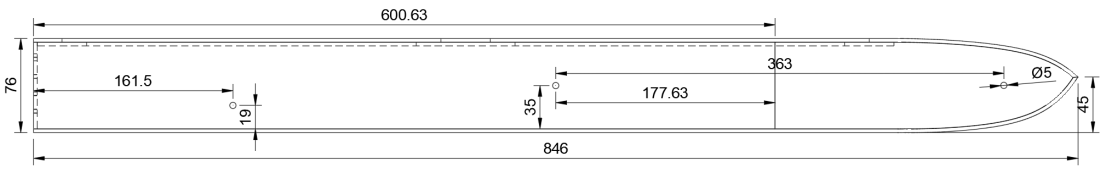


Figure 11: Side view drawing of the main body

Figure 11 displays the dimensions of the main body. It is 184.00 mm wide (out of the page) and the height was specifically chosen to ensure all components would fit inside.

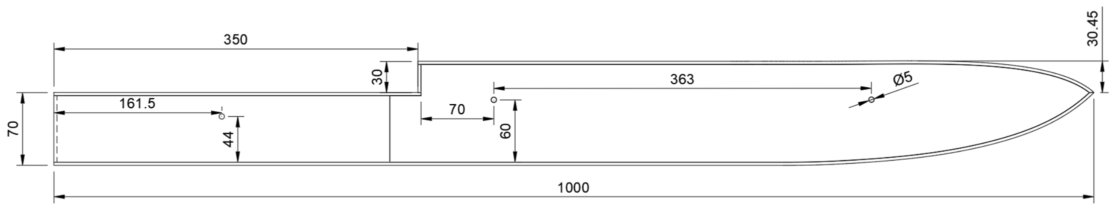


Figure 12: Side view drawing of the pontoon

Figure 12 demonstrates the pontoon dimensions. These are bigger than the main body to reduce the forward-facing profile of the craft (reducing drag) and to provide sufficient buoyancy. The pontoons are 100.00 mm wide (out of the page).

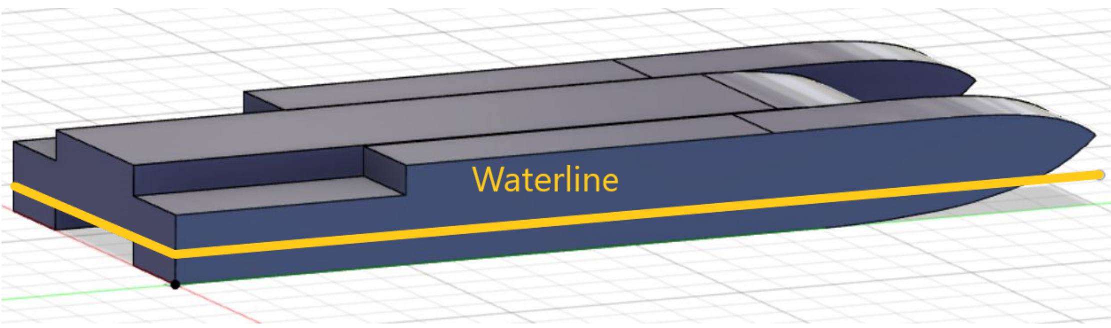


Figure 13: Expected boat waterline

An important part of the design phase is to calculate whether the boat displaces enough water to keep itself afloat, and if so, what the waterline is (what height of the hull is at the surface of the water). Using in-built Fusion360 tools, the combined volume of the hull was found to be 28.04 L. A safe estimate of the mass of the boat was 10.00 kg. To keep a mass of 10.00 kg afloat, the hull would need to displace 10.00 L of water. Given that it can displace a maximum of 28.04 L, the hull is clearly large enough to keep the boat afloat. The waterline of the boat is the height at which the submerged hull displaces water with an equal mass to the entire boat. Fusion360's volume tool was used empirically to determine that the waterline is 35.00 mm up from the bottom of the hull, shown in Figure 13. This is acceptable, as the waterline is below the middle of the front tapers, which ensures the hull will have a tendency to pitch up rather than down as it accelerates.

### 5.1.3 Material Selection and Budgeting

3.00 mm plywood sheets were used to build the hull. The primary reason for doing this is that it was the cheapest and most adequate sheet material available. Plywood was preferred due to its light mass (low density), high stiffness (while still being flexible enough to bend into a hull shape) and ease of cutting with a laser cutter. 3.00 mm plywood was chosen over 6.00 mm to minimise hull weight. It was expected that 3.00 mm plywood coated in resin would possess sufficient structural integrity, which the finite element analysis (FEA) proved. The final hull required 1.18 $m^2$ of 3.00 mm thick plywood. The manufacturer stated the plywood density was 900.00 $kg/m^3$, which results in a total mass of 3.20 kg for the empty wooden hull.

Figure 14: Fibreglass coated hull

Figure 15: Acrylic paint coated hull

A fibreglass and resin kit was used to coat the final hull. This kit contained 1.00 L of resin and 1.00 $m^2$ of matte fibreglass. The fibreglass and resin coated hull can be seen in figure 14.

Once the resin dried, the hull was coated in 400.00 g acrylic red gloss paint. This is shown in figure 15.

The estimated weight of the finished hull (including resin, fibreglass and paint) was 4.75 kg. The estimated weight of the assembled boat was 6.42 kg. A safety factor of around 1.5 was applied, so the mass of the entire boat during design calculations was assumed to be 10.00 kg

The total cost to manufacture the hull was $143.26, which was considered to be acceptable. An in-depth breakdown of cost and boat mass can be found in the appendix.

### 5.1.4 Structural Integrity

Fusion360's FEA tools were leveraged to conduct a static force analysis and ensure the hull was structurally sound. The hull was modelled as 3.00 mm thick sheets bonded together. The fibreglass was simulated by adding a 0.5 mm thick shell around the wood. A 98.00 N maximum force is applied through the front wings, and a 1.76 N force is applied through the back wings.

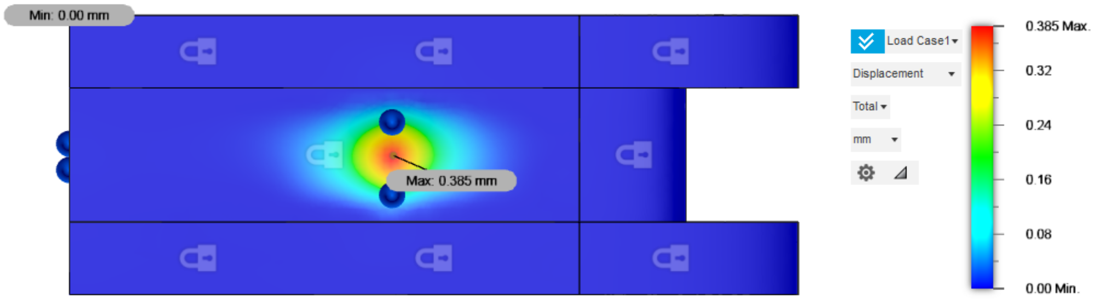


Figure 16: Fusion FEA analysis tool

As shown in figure 16, the maximum expected deflection is 0.385 mm. The safety factor is 10, which means the hull can withstand 10 times the expected stress without failure. This is considered acceptable.

## 5.2 Roll Control

### 5.2.1 Control Methodology

A PID controller was chosen as the control algorithm to keep the boat roll stable, as it is the simplest and most familiar one.

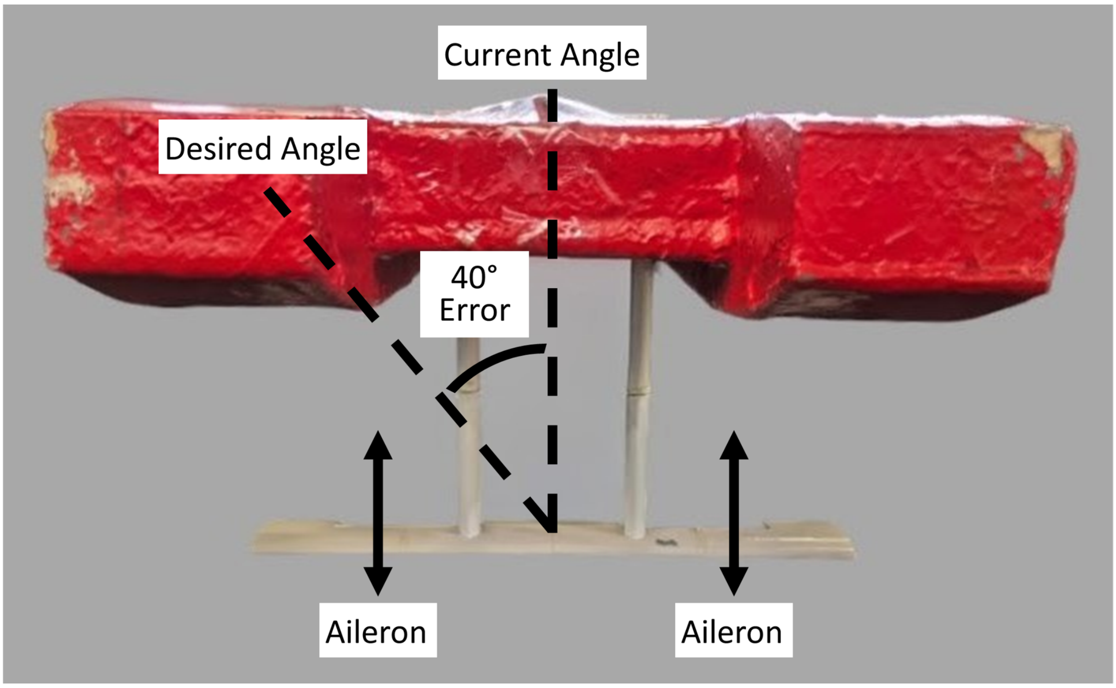


Figure 17: Roll control process/system explanation

The objective of the PID roll controller is to ensure the boat is able to roll quickly to a desired angular orientation and remain there. Figure 17 illustrates some key definitions. The boat's current angle is measured using the sensor. The setpoint is the angle the boat needs to be at. The error is the PID loop input, and it is defined as the difference between the setpoint and the current angle. The boats orientation can be controlled using the ailerons. The PID output is a numerical value that indicates how far the ailerons should be actuated to move the boat quickly to the desired orientation and maintain it.

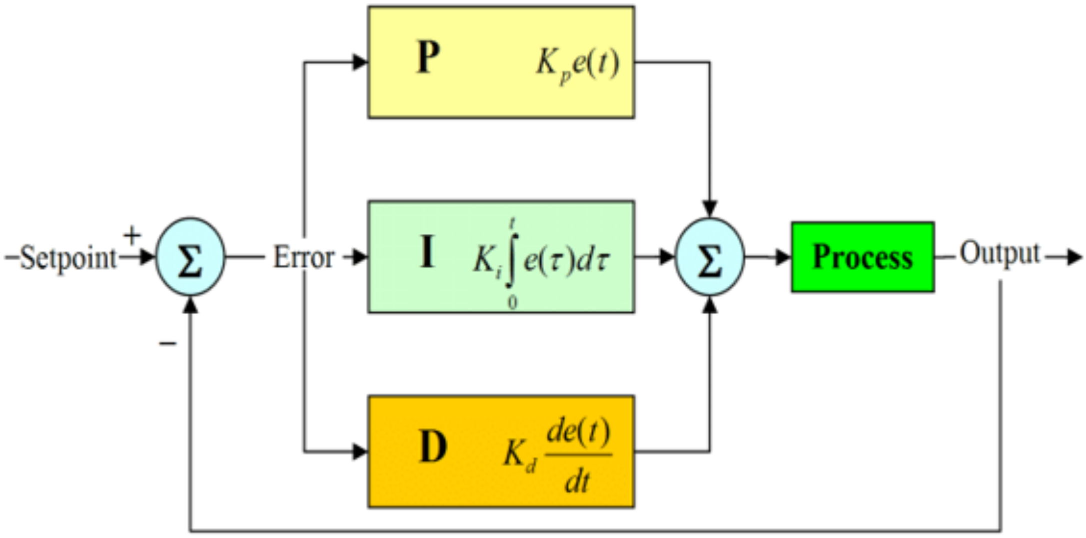


Figure 18: PID block/flow Diagram. [34]

The PID loop itself is made up of three main components, a proportional, an integral and a derivative component. This is shown in Figure 18. The proportional component looks at the present time and scales the output proportional to the current error. The integral component looks at the past by taking a sum (integral) of the previous error. The derivative component looks at the future by taking the derivative of the error. The PID loop is a mathematical formula, and the output of the three components are combined to yield a single output value that corresponds to how far the aileron should be actuated [35].

### 5.2.2 Hardware

Three main hardware components are required for the roll control of the boat. A microcontroller is used to program and implement the PID loop and associated logic. An IMU is used for the input, as it measures the boat's orientation. The output of the PID loop is used to control servos and move the ailerons.

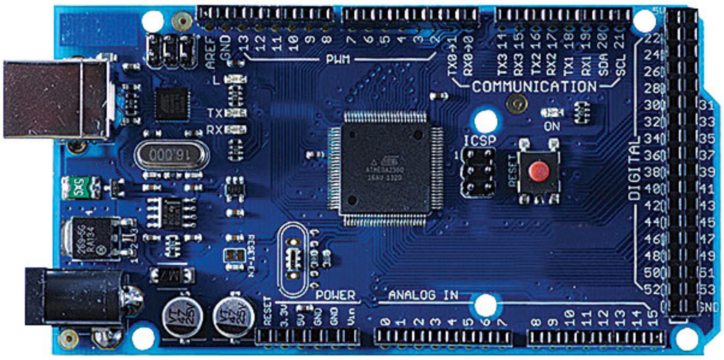


Figure 19: Arduino Mega microcontroller. [36]

As shown in Figure 19, an Arduino Mega was chosen as the primary microcontroller to implement the PID loop on. The Arduino infrastructure was chosen as these boards are very affordable, accessible and easy to program and work with. The board of choice was a Mega, as it was the only microcontroller with sufficient general purpose input/output (GPIO) pins to connect all the electronics.

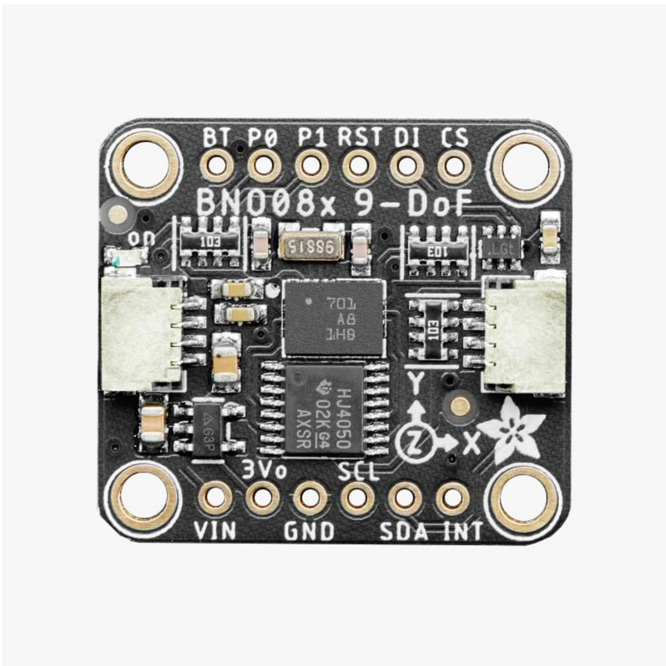


Figure 20: Adafruit BNO085 IMU. [37]

The IMU used was a BNO085 produced by Adafruit, which is shown in Figure 20. This is a 9-axis IMU with triple axis accelerometers, gyroscopes and magnetometers. The sensor fusion is handled by the board, which means that it is able to directly stream its roll, pitch and yaw orientation to the microcontroller. This was the primary reason for choosing this IMU, as it greatly simplifies the software.


Figure 21: DSServo DS3235. [38]

A servo is a simple electric rotary actuator that is able to rotate in a 180.00° arc and move to specific angles. This is why it was chosen to actuate the ailerons, as it is able to move the ailerons to precise and specific angles. The servos used are DS3235, manufactured by DSServo. It is shown in Figure 21.

### 5.2.3 Software

The initial software focused on testing the basic functionality of the boat, and so it established full manual control of the boat using a remote control. A Flysky FS-IA6B receiver was connected to the microcontroller, allowing it to receive inputs from a hand-held Flysky FS-i6x transmitter. This allowed the boat to be driven remotely by an operator and for the flaps to be manually controlled.

The PID loop is implemented as a function, which runs alongside the manual control of the craft. This allows the craft to be driven with the remote control, while the Arduino handles the roll control aspect.

It is important to carefully select the PID loop's cycle time, as this ensures the control loop is stabilising the boat fast enough. A cycle time of 50 Hz was considered adequate for this. Given the dynamics of the craft (the maximum and nominal rotation speeds) and the IMU data rate, this was considered to be fast enough to stabilise the boat while not demanding too much from the central processing unit (CPU).

The other important aspect of implementing a PID loop is storing data so that it can be used for debugging and tuning. It is critical to minimise the load on the CPU during operation. As such, streaming data during testing is not feasible since the CPU is quite slow at this. Instead, the data is stored in a large array (the CPU is very fast at storing data) and then streamed over WiFi once testing is complete. Due to the Arduino Mega's limited random access memory (RAM) size of 8.19 kB, it was necessary to minimise and compress stored data. As such, only the boat's current orientation and PID loop output can be stored at each cycle.

The full software can be found in the appendix.

### 5.2.4 Testing and Tuning

The difficult part when implementing a PID loop is tuning it. This consists of determining the integer gain values for the three PID components to ensure the PID loop has the desired response. The technique used to tune the PID loop is manual tuning. This is done by graphing the boat's orientation over time, analysing the graph and then "manually" adjusting the P, I and D gains until desirable behaviour is achieved [39].

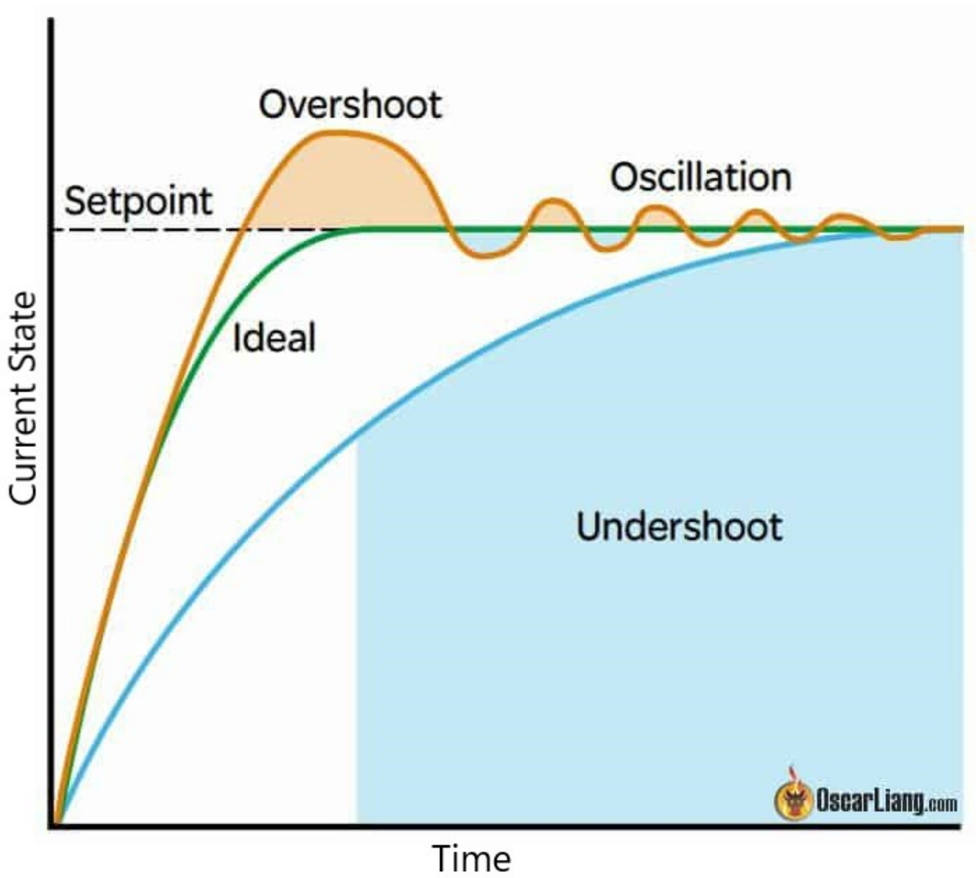


Figure 22: Graph of the ideal PID loop performance. Adapted from [40]

The ideal PID behaviour is illustrated in Figure 22. A correctly tuned PID loop will reach the setpoint quickly and then stay there without oscillations. If the PID loop is not properly tuned, it will overshoot the setpoint and then oscillate around it, or it will undershoot by taking too long to reach the setpoint.

The first step in manual tuning is to set the I and D gains to 0, and tune the P gain. Initially, a small value is tested, and this is slowly increased until the system has a fast response and the output is close to the setpoint (without causing oscillations). The I gain is then tuned to remove the steady state error. A D gain can then be added if necessary (to increase response speed without introducing oscillations). Each test was completed by driving the boat in a straight line while the hull rose out of the water. Due to the short distance of the testing environment, the tests lasted for around 12 seconds [39].

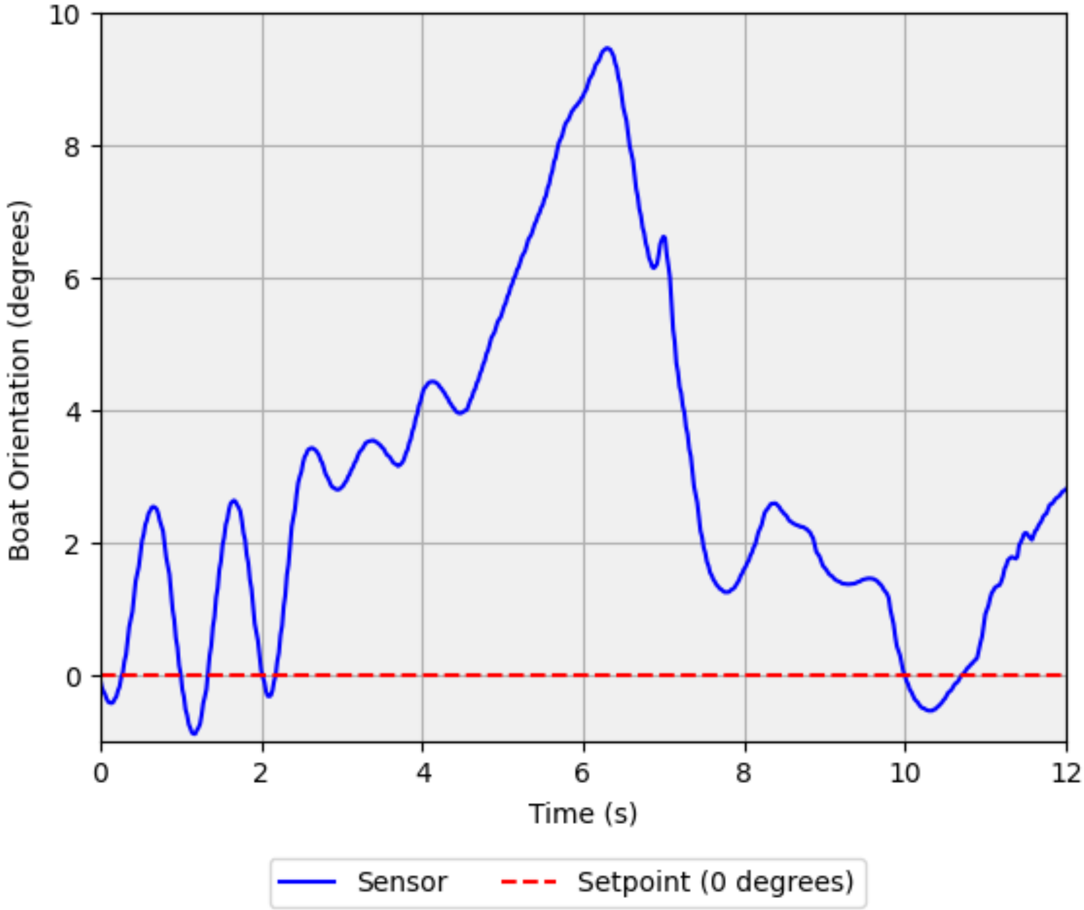


Figure 23: Boat orientation over time with a P gain of 800

The initial P value of 800 was calculated based on a maximum error estimate and the required output, though it was decreased to ensure it was a small and conservative (safe) starting value. As seen in Figure 23, the boat should stay at the setpoint of $0.00^{\circ}$. However, it drifts quite far from the setpoint and possesses some undesirable oscillatory behaviour. This large drift is to be expected with the low P gain, as this value causes the controller to respond quite slowly to error. For the next test, the P gain was increased so that the controller would respond faster to the error.

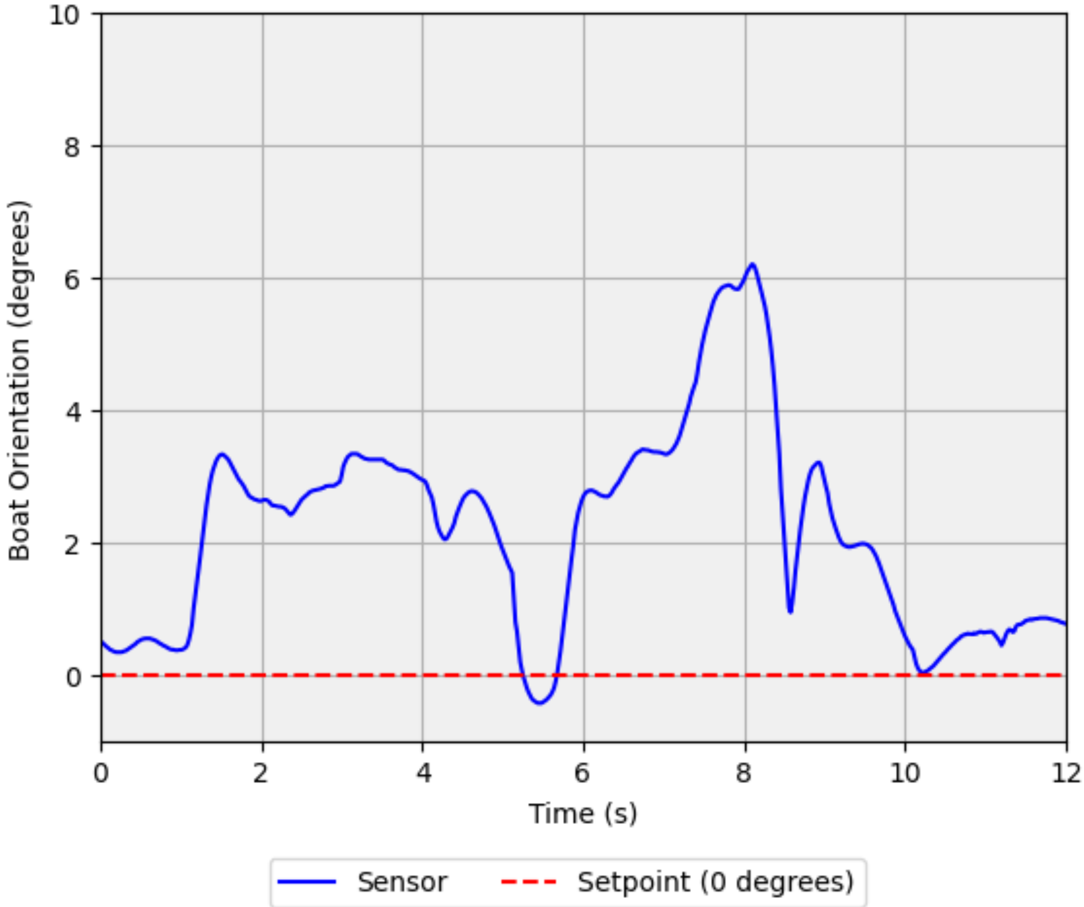


Figure 24: Boat orientation over time with a P gain of 1200

Figure 24 illustrates the second completed test. The behaviour is similar to Figure 23, but the maximum drift has decreased, which is to be expected. However, with such a large PID value, it was calculated that the orientation shouldn't drift far and the boat should be oscillating around the setpoint. The poor stability indicates the possibility of hardware issues that are affecting the PID loop, but another test was still conducted with an even higher P gain.

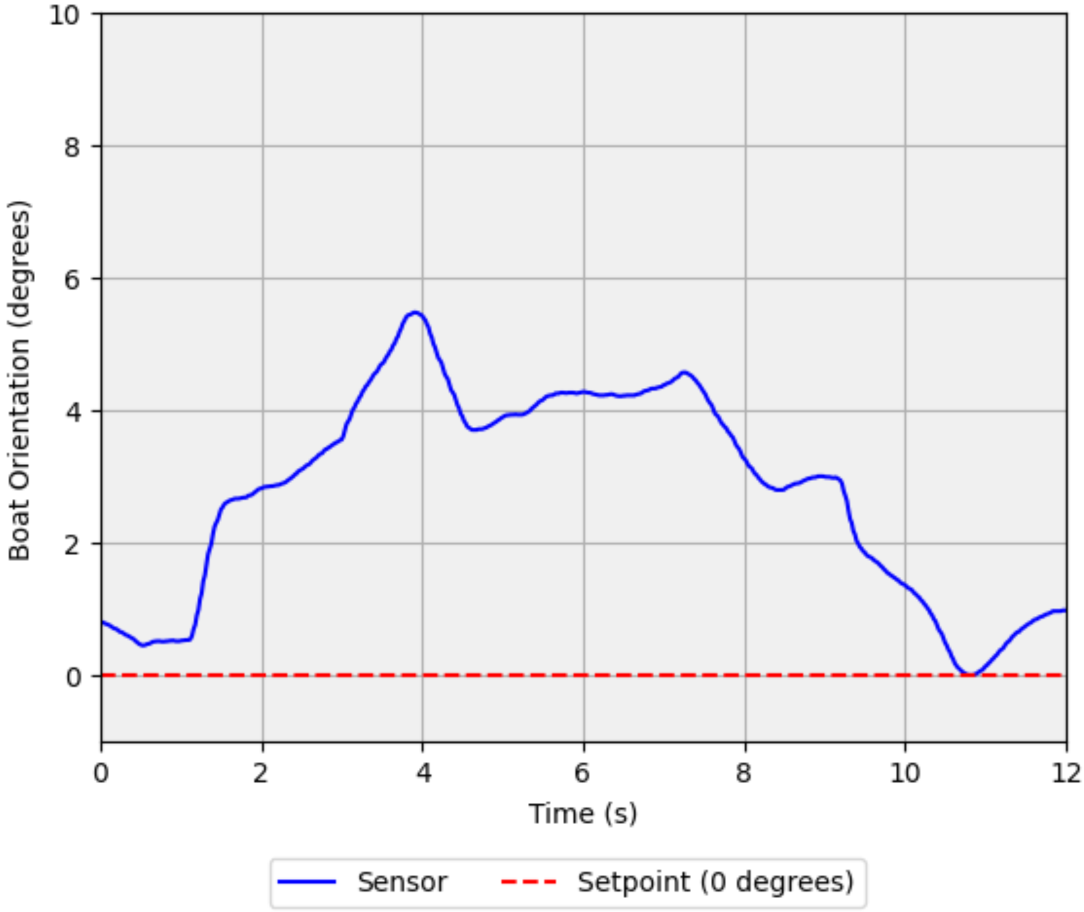


Figure 25: Boat orientation over time with a P gain of 1500

Figure 25 demonstrates the final test conducted. The P gain was very high, and the drift has again decreased slightly. However, the high P gain should have resulted in the boat oscillating around the setpoint without such a large drift. The aileron actuation design had been revised several times, and the results of this PID test indicated that there was an issue with that system. It was found that the aileron's upward travel was severely limited due to a design flaw, which limited the control on the boat's orientation.

This design flaw is reflected in the PID loop. As the P gain is quite high, the control algorithm is attempting to correct the error early and moving the ailerons quickly. However, the boat is slow to roll back in the opposite direction because the ailerons are unable to move far enough.

An analysis of the design issue revealed that it would take too long to fix, and so testing was concluded early as no amount of tuning the control algorithm would alleviate the hardware issue. The aim was to test and implement a full PID loop, but due to this issue, only a P controller was able to be implemented and tested.

## 5.3 Heading Control

### 5.3.1 Control Methodology

The control methodology for this controller is almost identical to the roll control, and so will not be re-explained here. A PID controller was used, except the controller is being used to keep the boat at a constant compass heading. The boat's yaw orientation (heading) is controlled using a rudder.

### 5.3.2 Hardware

In a similar manner to the roll control, three hardware components are required to achieve the heading control.

The heading control software runs on the Arduino Mega, alongside the roll control software. The IMU is able to provide the Arduino Mega with a yaw orientation referenced from true north. A DS3235 servo is also used to actuate the rudder and thus steer the boat.

### 5.3.3 Software

As the applications are very similar and the roll control software was successful, the same approach was used here. A separate function was defined to handle the heading control PID loop, also operating at a cycle time of 50 Hz. The data transfer worked in the same way, with the Arduino Mega recording the boat's compass orientation and heading PID output and then streaming it over WiFi.

### 5.3.4 Testing and Tuning

The exact same tuning principle and methodology from the roll control were used here.

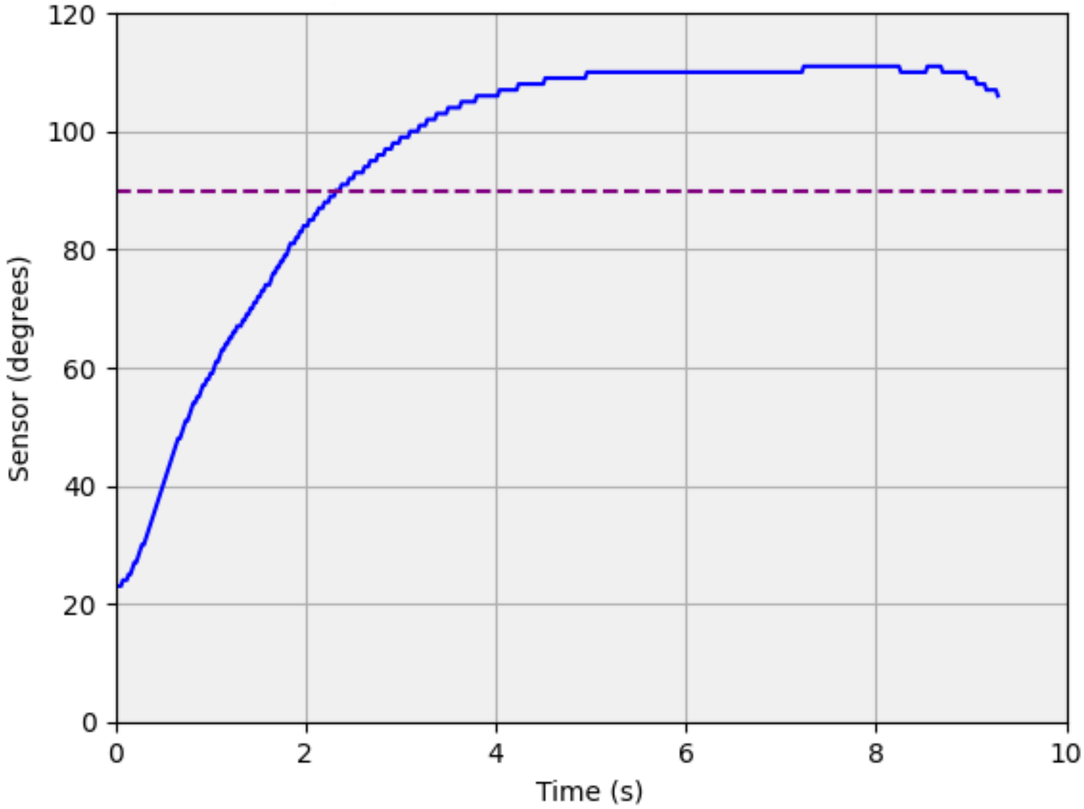


Figure 26: Boat compass heading over time with a P gain of 4

The initial P gain of 4 was also determined through calculations and then reduced slightly to ensure a safe starting value. This P gain value is significantly smaller, as the controller for the heading needs to be a lot less sensitive to error than the roll controller. As shown in Figure 26, the setpoint is a 90.00° orientation, which is east. Unlike the roll control, this graph demonstrates fairly ordinary behaviour for a P controller. The only difference is that the low P gain should have resulted in a large amount of undershoot rather than the overshoot shown in the graph. The P gain was increased for the next test.

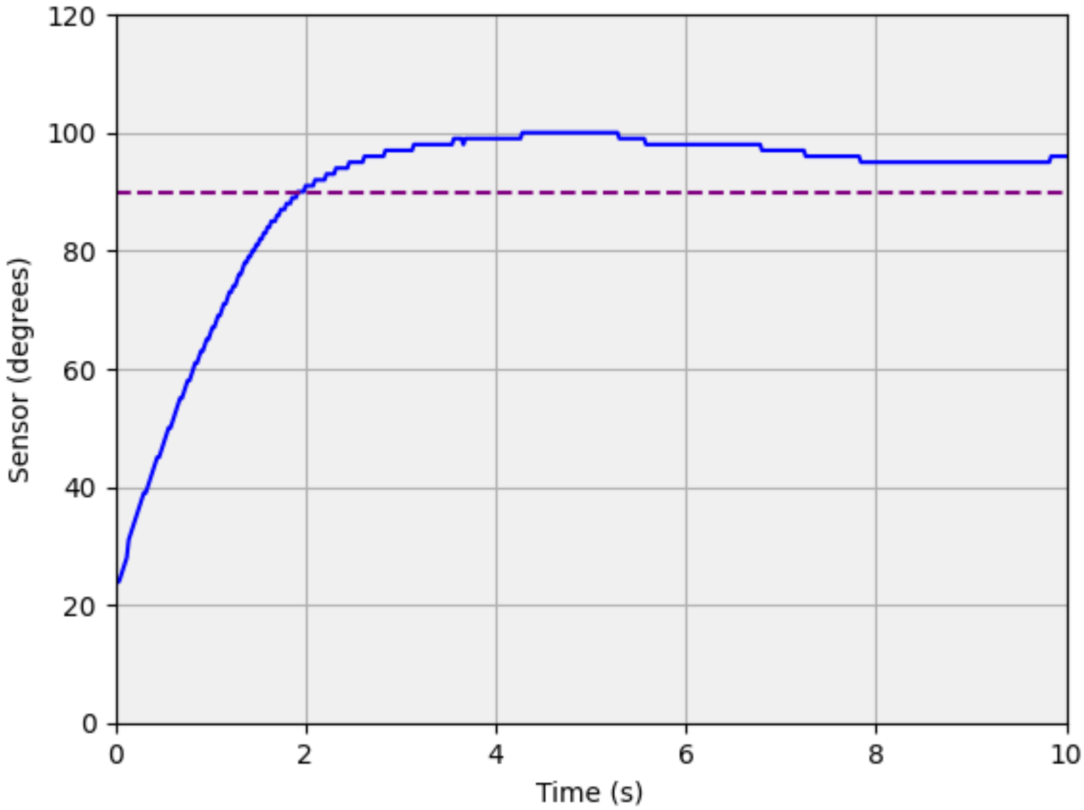


Figure 27: Boat compass heading over time with a P gain of 12.5

Figure 27 illustrates the results of the second test. The overshoot is significantly less than the previous graph, which indicates that increasing the P gain reduces the overshoot. This is unconventional, as typically increasing P gain will increase overshoot. However, it was determined that this is due to the behaviour of the boat when the rudder is turned. Once the boat is turning, the rudder needs to countersteer (turn the other way) to get the boat to level out and move straight again. This is why the higher P gain reduced overshoot, as it is turning the rudder and counter-steering earlier (since it is more sensitive to a smaller error).

As such, a higher P gain was tested next to further decrease overshoot.

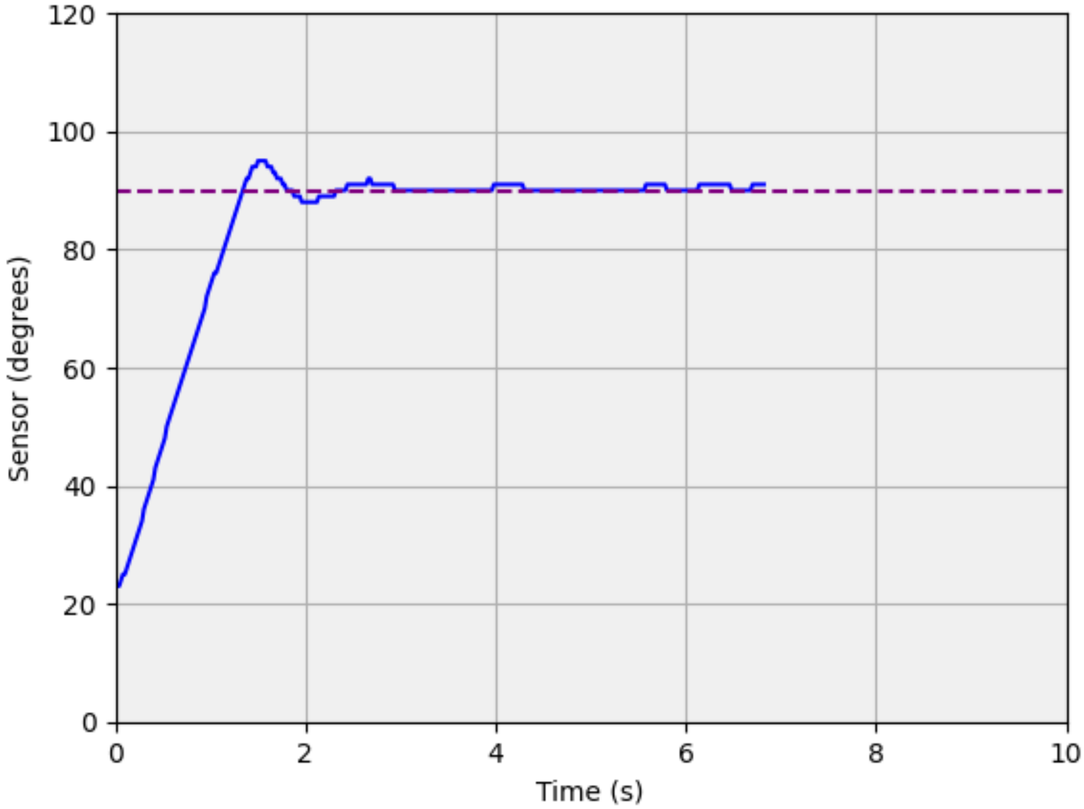


Figure 28: Boat compass heading over time with a P gain of 45

The third test can be seen in Figure 28. The graph demonstrates that the higher P gain was successful in drastically reducing the overshoot. The behaviour in this graph is very close to the desired behaviour, with the boat reaching the setpoint very quickly and then remaining there without significant oscillation. This was the last test completed, as the behaviour exhibited here was suitable to be used in autonomous driving and so the next tests focused on building on this software and implementing waypoint driving.

It would have been desirable to conduct further tests after the waypoint driving had been implemented, as the goal was to implement a complete PID loop, not just a P controller. Unfortunately, this was not possible, as a microcontroller failure during a later test caused a fault in some of the electronics. However, the behaviour of this control loop could have been improved by reducing the P gain. Decreasing the P gain will reduce the initial oscillations, and an I gain along with a D gain can be used to reduce the overshoot and track the setpoint without any steady state error.

## 5.4 Overall outcome

Figure 29: Front-side view of the final boat

The completed boat is shown in Figure 29. The hull construction went as planned, except for a minor issue that involved trimming the noses of the three pieces. This was done because the roof and floor plywood pieces were unable to bend enough, so the curvature of the pointed ends needed to be reduced. The hull has performed as expected from the calculations and design requirements (including the expected strength, mass and waterline).

Figure 30: Bird's eye view of the final boat

Figure 30 displays the electronics installed in the hull. The integration and programming of these electronics was successful, with full remote control of the boat being achieved. The earlier stages of the project were completed successfully, but the limited time frame, large scope and difficult project prevented the completion of the later stages and overall objectives of the project.

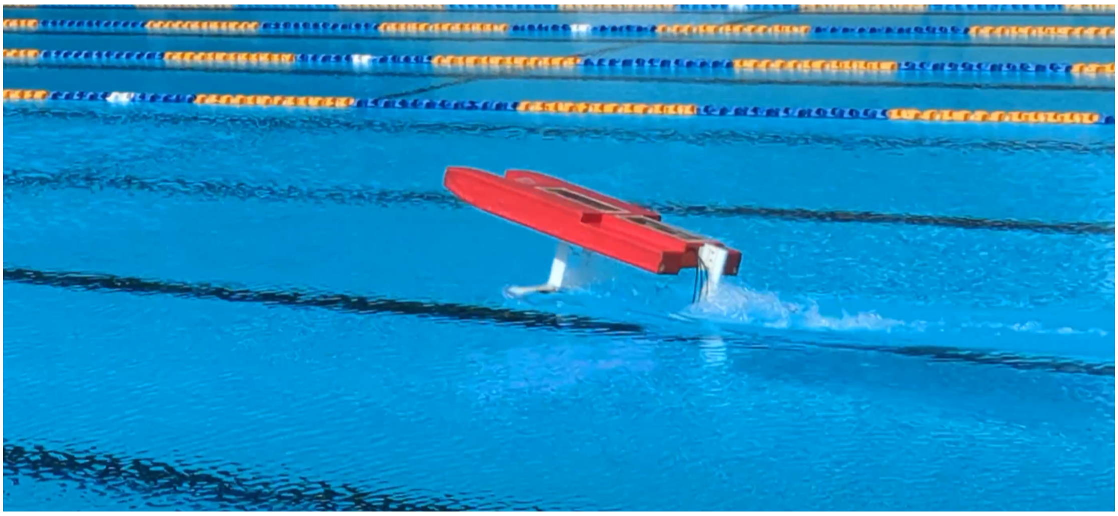

Figure 31: Final boat hydrofoiling

The hydrofoil boat was able to foil, with the hull of the boat successfully rising out of the water. This is shown in Figure 31. Control software was implemented to ensure the boat remained pitch and roll stable. The software itself was successful and worked as expected, but the craft wasn't stable due to the aforementioned hardware issue with the ailerons

As the boat was unable to sustain a foiling state, the autonomous driving was implemented when the hull was on the surface of the water (as a regular boat). This was successful, with the boat being able to closely follow a desired heading. The heading control loop was implemented alongside the heading calculation algorithm, which were successful in driving the craft between GPS waypoints.

## 5.5 Limitations

This project suffered from two main limitations that caused the timeline of the project to blow out.

### 5.5.1 Propulsion Issues

The initial design used a submerged 500 W thruster to provide propulsion. This was chosen based on previous experience stating that a 20.00 km/h top speed would be attainable and the fact that it was already available without requiring purchase. However, experimental testing demonstrated that the thruster was not powerful enough to reach foiling speed. This issue was alleviated by designing and building a thruster using a 1600 W, 2000 KV brushless motor and a custom-designed 3D printed propeller. The hydrofoil boat was now fast enough to reach foiling speed, but this complication caused significant time to be lost.

This new thruster also introduced its own problems. The large and heavy hydrofoil boat requires a low revolutions per minute (RPM) and high torque motor. However, the 2000 KV motor specifications are the opposite of this, which results in the motor being heavily overworked and the cables overheating. As such, the boat could only be tested continuously for 2-5 minutes at a time, after which testing was forced to stop so the cables could be cooled.

### 5.5.2 Aileron Travel Issue

The other key issue was the aforementioned aileron travel issue, which greatly limited the control of the craft. While the ability to control the roll was reduced, the main issue was with the pitch control. The ailerons are able to move all the way down, but not very far up. This means the hull is able to rise out of the water, but the ailerons are unable to stop the boat from rising and stabilise the altitude. This causes the boat to fall over shortly after foiling. Due to the limited time frame and the time lost with the propulsion issue, this problem was detected too late in the project.

# 6 Conclusion

This project was partially successful in meeting its objectives.

The boat, software and electronics are fully working, with manual, semi-autonomous and autonomous driving capabilities. The only limitation of the current boat is with the hardware, specifically the ailerons, which prevent proper control once foilborne. However, the boat in its current state can still be used to test different wing, mast and aileron designs, as all the other aspects are operating as expected. The boat is easy to use for testing, as it is relatively small and lightweight. Overall, it is partially usable as a hydrofoil technology testbed, being able to research different hardware changes.

The autonomous driving was not implemented to the degree that was desired in the objectives, as it should also have been able to operate when the boat is foilborne. However, the autonomous driving algorithms and electronics implemented still present a good starting point for autonomous driving in hydrofoils. The developed software can be expanded upon to drive the boat once it is foilborne, creating a platform that can be used for further research and implementation of more advanced and robust autonomous driving algorithms.

The main items for future work would be to fix the two limitations previously mentioned. Now that the boat has been constructed, the thrust required to reach the foiling velocity can be experimentally determined. From this, the correct specifications for the motor and propeller can be calculated, allowing these to be purchased and installed to eliminate the overheating issues. The aileron issue can be alleviated by expanding on the current design to implement a different actuation mechanism that will improve the aileron travel. New wings, masts and ailerons can then be fabricated and installed. After this, the control loops can be re-tuned, which will allow the hydrofoil boat to sustain stable flight.

While unsuccessful in fully achieving the objectives, this project has made substantial progress, developing the foundations of a good hydrofoil craft and laying the groundwork for future projects and testing at UWA in this area. The design was carefully developed based on the success and failure of existing designs in the literature and industry. The construction method and materials ensure the longevity and durability of the hull, allowing it to be used for future projects and testing. The final boat possesses fully working software and electronics. Testing has indicated that the design of the hydrofoil is sound, and only a small amount of redesign and rework is required to fully meet the objectives and bring the hydrofoil to the level that was expected at the beginning of the project. This can then be used as a platform for future research and testing to develop more sustainable, efficient and autonomous hydrofoils.

# 7 References


[1] H. Song, Y. Lee, G.-S. Seo and D. Won, 'Electric vehicle charging management in smart energy communities to increase renewable energy hosting capacity,' in *2023 11th International Conference on Power Electronics and ECCE Asia (ICPE 2023 - ECCE Asia)*, 2023, pp. 453–458. DOI: 10.23919/ICPE2023-ECCEAsia54778.2023.10213800.

[2] N. Hashemi Taba, A. Heidari, N. Haddadian and S. Rezaeian, 'Sustainable urban development through reducing green house emissions: A new framework for replacing fossil-fuel vehicles with electronic vehicles,' in *2019 IEEE Conference on Sustainable Utilization and Development in Engineering and Technologies (CSUDET)*, 2019, pp. 23–28. DOI: 10.1109/CSUDET47057.2019.9214629.

[3] W. D. Grossmann, I. Grossmann, K. W. Steininger and L. Magaard, 'Oceans and new renewable energy systems,' in *OCEANS'11 MTS/IEEE KONA*, 2011, pp. 1–4. DOI: 10.23919/OCEANS.2011.6107088.

[4] United Nations, *Climate Action*, [Accessed: 2024-05-06]. [Online]. Available: https://www.un.org/en/climatechange.

[5] United Nations Climate Change, *The Paris Agreement*, [Accessed: 2024-05-06]. [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement#:~:text=Its%20overarching%20goal%20is%20to,above%20pre%2Dindustrial%20levels.%E2%80%9D.

[6] Department of Climate Change, Energy, the Environment and Water, *Net Zero*, [Accessed: 2024-05-06]. [Online]. Available: https://www.dcceew.gov.au/climate-change/emissions-reduction/net-zero.

[7] *The International Maritime Organization's Initial Greenhouse Gas Strategy*, 2018. [Online]. Available: https://theicct.org/publication/the-international-maritime-organizations-initial-greenhouse-gas-strategy/.

[8] Candela, *Candela C-7*, [Accessed: 2024-05-06]. [Online]. Available: https://candela.com/candela-c-7/.

[9] S. Doyle, *The Measure of The Candela Seven*. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9450313.

[10] C. Forlini, R. Qayyum, M. Malej *et al.*, 'On the problem of modeling the boat wake climate; the florida intracoastal waterway,' eng, *Journal of geophysical research. Oceans*, vol. 126, no. 2, 2021, ISSN: 2169-9275.

[11] D. Herbert, E. Astrom, A. C. Bersoza *et al.*, 'Mitigating erosional effects induced by boat wakes with living shorelines,' eng, *Sustainability (Basel, Switzerland)*, vol. 10, no. 2, pp. 436–, 2018, ISSN: 2071-1050.

[12] P. Magini and J. Burroughs, 'Control of the hydrofoil ship,' eng, *Journal of navigation*, vol. 20, no. 3, pp. 292–303, 1967, ISSN: 0373-4633.

[13] U. N. C. on Trade, *Review of Maritime Transport 2018*, eng. New York City: United Nations Publications, 2018, pp. 101–, ISBN: 9211129281.

[14] Flitetest, *AIRFOILS AND AERODYNAMICS - A BASIC OVERVIEW*, [Accessed: 2024-05-13]. [Online]. Available: https://www.flitetest.com/articles/Airfoils_Aerodynamics_A_Basic_Overview.

[15] Modelshipmaster, *BOEING JETFOIL scale model*, [Accessed: 2024-05-13]. [Online]. Available: https://www.modelshipmaster.com/products/other_types/Boeing-jetfoil.htm.

[16] D. Speranza, S. Papa, C. Pensa and R. Di Bernardo, 'Hydrofoil technology: Current applications and future developments for sustainable boating,' eng, in *Lecture Notes in Mechanical Engineering*, 2024, pp. 339–346, ISBN: 9783031520747.

[17] Candela, *Electric Hydrofoiling - The Future*, [Accessed: 2024-05-06]. [Online]. Available: https://candela.com/.

[18] BMW, *THE ICON - innovative tides*, [Accessed: 2024-05-06]. [Online]. Available: https://www.bmw.com/en/electric-future/the-icon-electromobililty-on-the-water.html.

[19] Artemis Technologies, *Artemis eFoiler*, [Accessed: 2024-05-06]. [Online]. Available: https://www.artemistechnologies.co.uk/efoiler/.

[20] W. Weist, 'Development of an ultrasonic ranging device for hydrofoil height control,' in *Ocean 73 - IEEE International Conference on Engineering in the Ocean Environment*, 1973, pp. 438–444. DOI: 10.1109/OCEANS.1973.1161221.

[21] J. Bai and Y. Kim, 'Control of the vertical motion of a hydrofoil vessel,' eng, *Ships and offshore structures*, vol. 5, no. 3, pp. 189–198, 2010, ISSN: 1744-5302.

[22] J. Ren and Y. Yang, 'Fuzzy gain scheduling attitude control for hydrofoil catamaran,' in *Proceedings of the 2004 American Control Conference*, vol. 2, 2004, 1103–1108 vol.2. DOI: 10.23919/ACC.2004.1386719.

[23] Y. Wang, L. Bai and S. Liu, 'Nonlinear control of hydrofoil catamaran course in three dof,' in *2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific)*, 2014, pp. 1–6. DOI: 10.1109/ITEC-AP.2014.6940619.

[24] S. Liu, C. Xu and Y. Wang, 'Disturbance rejection control for the course keeping of the fully-submerged hydrofoil craft,' in *2016 35th Chinese Control Conference (CCC)*, 2016, pp. 747–751. DOI: 10.1109/ChiCC.2016.7553174.

[25] M. A. H. Tarif, Z. Z. Zakaria, D. S. Laila, M. A. M. Sarbini and S. R. Ya'Akub, 'Design and control of an autonomous electric catamaran boat,' in *2022 International Conference on Green Energy, Computing and Sustainable Technology (GECOST)*, 2022, pp. 75–80. DOI: 10.1109/GECOST55694.2022.10010362.

[26] M. Noorizadeh and N. Meskin, 'Design of small autonomous boat for course-keeping manuevers,' in *2017 4th International Conference on Control, Decision and Information Technologies (CoDIT)*, 2017, pp. 0908–0912. DOI: 10.1109/CoDIT.2017.8102712.

[27] F. Le Bars and L. Jaulin, 'The world robotic sailing championship, a competition to stimulate the development of autonomous sailboats,' in *OCEANS 2015 - Genova*, 2015, pp. 1–5. DOI: 10.1109/OCEANS-Genova.2015.7271767.

[28] D. S. dos Santos, C. L. Nascimento and W. C. Cunha, 'Autonomous navigation of a small boat using imu/gps/digital compass integration,' in *2013 IEEE International Systems Conference (SysCon)*, 2013, pp. 468–474. DOI: 10.1109/SysCon.2013.6549924.

[29] A. Widaryanto and B. Kusumopotro, 'Modeling and designing direct inverse control using back-propagation neural network for skid steering boat model,' in *2019 IEEE International Conference on Innovative Research and Development (ICIRD)*, 2019, pp. 1–5. DOI: 10.1109/ICIRD47319.2019.9074761.

[30] R. P. Dewi, T. Asfihani and H. Nurhadi, 'Design control of autonomous surface vehicle position using proportional integral derivative method,' in *2021 International Conference on Advanced Mechatronics, Intelligent Manufacture and In-*

*dustrial Automation (ICAMIMIA)*, 2021, pp. 131–136. DOI: 10.1109/ICAMIMIA54022.2021.9807778.

[31] S. Liu, C. Xu and L. Zhang, 'Hierarchical robust path following control of fully submerged hydrofoil vessels,' *IEEE Access*, vol. 5, pp. 21 472–21 487, 2017. DOI: 10.1109/ACCESS.2017.2756852.

[32] Littohot Team, *36" RC EP Epoxy Fiberglass Catamaran Racing Boat Hull - White*, [Accessed: 2024-10-13]. [Online]. Available: https://www.aliexpress.com.

[33] Pro Boat, *Blackjack 42inch Racing Catamaran*, [Accessed: 2024-05-12]. [Online]. Available: https://www.metrohobbies.com.au/products/pro-boat-blackjack-42-inch-8s-brushless-rc-catamaran-black-orange-prb08043t1.

[34] V. Bondar, W. Ehsan, M. Beg *et al.*, 'Beam position feedback system supported by karabo at european xfel,' Jan. 2019. DOI: 10.18429/JACoW-ICALEPCS2019-MOPHA040.

[35] MIT, *16.06 Principles of Automatic Control Lecture 10*, [Accessed: 2024-09-30]. [Online]. Available: https://ocw.mit.edu/courses/16-06-principles-of-automatic-control-fall-2012/d534f7b9322ae4439af5f23889ea074c_MIT16_06F12_Lecture_10.pdf.

[36] Altronics, *Funduino Mega 2560 R3 Arduino Compatible Development Board*, [[Accessed: 2024-09-30]. [Online]. Available: https://www.altronics.com.au/p/z6241-funduino-mega-2560-r3-compatible-development-board/.

[37] ArduSimple, *Adafruit 9-DOF Orientation IMU Fusion Breakout – BNO085*, [Accessed: 2024-09-30]. [Online]. Available: https://www.ardusimple.com/product/adafruit-9-dof-orientation-imu-fusion-breakout-bno085/.

[38] Amazon, *Hosyond DS3235 35kg Digital RC Servo High Torque All Metal Gear Coreless Motor Waterproof Servo Motors for RC Robot, Car, Truck (Control Angle 270°)*, [[Accessed: 2024-09-30]. [Online]. Available: https://www.amazon.com.au/Hosyond-Digital-Coreless-Waterproof-Control/dp/B0CJFR6KV9?th=1.

[39] T. Bräunl, *Embedded robotics : from mobile robots to autonomous vehicles with Raspberry Pi and Arduino*, eng, Fourth edition. Singapore: Springer, 2022, ISBN: 9789811608049.

[40] Oscar Liang, *FPV Drone PID Explained – Mastering Flight Performance through PID Tuning*, [Accessed: 2024-09-30]. [Online]. Available: https://oscarliang.com/pid/.

# 8 Appendices

## 8.1 Appendix A: Cost and Weight Breakdown

Table 1: Cost and Weight Breakdown by Component

| Part | Vendor | Part Name and Description | Quantity | Price ($) | Mass (g) |
|---|---|---|---|---|---|
| Electronic Speed Controller | Aliexpress | SC8 RTR, 120A 4s waterproof esc | 1 | 80.31 | 113 |
| ESC Extension cable | Aliexpress | 12 AWG, 200° black silicon cable | 1 metre | 18.91 | 91 |
| 1600 watt brushless motor | Aliexpress | Rocket 2000KV 4074 brushless | 1 | 110.45 | 380 |
| LiPo Battery | Aliexpress | 10400mAh, 60C 4s Lithium-Polymer | 1 | 97.00 | 732 |
| Step Down Buck Converter | Aliexpress | 300W, 20A, DC-DC converter | 1 | 6.37 | 40 |
| Aileron Connector | Aliexpress | Pushrod Servo Connector | 2 | 10.76 | 4 |
| Aileron Pushrod | Aliexpress | 304 Stainless Steel 2mm Diameter | 1 metre | 1.74 | 25 |
| Waterproof servo | Aliexpress | Waterproof DS3230, 30kg servo | 3 | 105.48 | 200 |
| Handheld Transmitter | Aliexpress | Flysky FS-i6x 2.4 GHz | 1 | 94.29 | N/A |
| Receiver | Aliexpress | FS-IA6B Portable Receiver 2.5GHz | 1 | 21.44 | 15 |
| Arduino Microcontroller | Core Electronics | Arduino Mega 2560 | 1 | 76.95 | 37 |
| Wifi Arduino Board | Altronics | ESP8266-ESP-12F Board | 1 | 21.95 | 20 |
| Inertial Measurement Unit | Core Electronics | Adafruit 9DOF BNO085 | 1 | 49.25 | 5 |
| Ultrasonic Distance Sensor | Aliexpress | HC-SR04 Ultrasonic sensor | 1 | 4.12 | 9 |
| Wood Glue | Bunnings | Parfix PVA adhesive wood glue | 1 | 13.13 | 150 |
| Plywood Sheets | Bunnings | 3mm thick plywood premium | 3 | 54.00 | 3200 |
| Resin Fibreglass Kit | Bunnings | Protite 1kg fibreglass resin kit | 1 | 56.13 | 1000 |
| Red Paint | Supercheap Auto | Polycraft acrylic red spray paint | 1 | 20.00 | 400 |
| Total Mass Without Safety | N/A | Mass of craft without safety factor | N/A | N/A | 6421 |
| Safety Factor Mass | N/A | Safety factor is ~1.5 | N/A | N/A | 3579 |
| Total Mass with Safety | N/A | Mass of craft with safety factor | N/A | 842.28 | 10000 |