University of Western Australia

Engineering Honours Research Project

Developing Control and Navigation Algorithms for a Model Autonomous Hydrofoil

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Abstract

The maritime industry faces increasing challenges related to fuel consumption, emissions, and overall operational efficiency, driven by a requirement to meet the International Maritime Organization's (IMO) greenhouse gas reduction targets by 2050. In response, there has been a growing interest in hydrofoil technology because compared to traditional vessels they have reduced water resistance and drag, and they can lower fuel consumption by up to 80%. However, their implementation poses challenges in ease and complexity of control and manoeuvrability.

This research focuses on the development of control and navigation algorithms for a remote-controlled model autonomous hydrofoil, to advance the understanding of a hydrofoil's operational control and integration with modern automation technologies. The study seeks to optimize the hydrofoil design through mathematical simulations, fabricate a prototype, and implement advanced control algorithms to achieve precise height and pitch control. Furthermore, the research explores the integration of way-point navigation and path-planning algorithms to enhance autonomous operations.

The methodology encompasses a combination of mathematical simulations, experimental testing, and iterative software development for control and automation. Initial findings suggest that while hydrofoils incur higher upfront energy and maintenance costs, they provide significant long-term benefits in fuel efficiency and overall performance. The incorporation of advanced control systems and autonomous navigation capabilities enhances both operational ease and efficiency, particularly for long-distance and passenger-carrying vessels.

In conclusion, this research contributes to the advancement of hydrofoil technology by addressing key challenges in design, control, and automation, thereby paving the way for more sustainable and efficient maritime transportation solutions.

Contents

1 Introduction

The shipping and boating industry has long faced challenges related to high fuel consumption, emissions, and overall efficiency, prompting the International Maritime Organization (IMO) to adopt a resolution for a greenhouse gas (GHG) strategy [1]. This strategy, aiming for significant GHG reduction targets by 2050, highlights the need for improved fuel efficiency and the development of low and zero-carbon fuels, as well as propulsion technologies which can be seen in Figure 1.1. However, electrifying small vessels presents difficulties due to battery limitations [2].

Type	Years	Measure	Target	Current status
Short-term	2018-2023	New Energy Efficiency Design Index (EEDI) phases	New vessels	-10% in 2015 -20% in 2020 -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 1.1: Candidate measures included in IMO's initial GHG strategy [1]

To address these challenges, attention has turned to hydrofoils [2]. Hydrofoils, with their aerodynamic design, generate lift force when travelling at speed, reducing resistance components, and enabling higher speeds with less fuel or electricity consumption. The Swedish company Candela's success in integrating hydrofoils into electric vessels highlights their superior energy efficiency compared to traditional hulls. The foils help reduce water friction and the drag caused by waves slamming into the hull of the boat, this reduces energy consumption by 80% when compared to normal internal combustion engine boats [3].

In addition, the global ferry industry transports approximately 4.27 billion passengers and 373 million vehicles annually [4]. Heavily regulated by organizations like the IMO, this industry must meet strict safety, environmental, and security standards, which include vessel design and operational inspections. Recent advancements in automation, such as Automation 2.0, hold potential to revolutionize the passenger ferry industry. Automated ferries could enhance safety, optimize route efficiency, and minimize human error, making hydrofoil-equipped ferries a more viable, environmentally friendly, and efficient form of water transport.

Hydrofoils represent a promising solution for improving efficiency in the maritime industry, particularly when integrated with advanced automation technologies. This project aims to develop a platform to investigate the control systems required to stabilize hydrofoils, while also exploring the extent to which hydrofoils can be automated. By addressing the challenges of fuel consumption, emissions, and manoeuvrability, hydrofoils could play a significant role in creating a more sustainable and efficient future for maritime transportation and recreational boating.

2 Problem Overview and Project Aims

2.1 Problem Identification

The maritime transportation industry faces significant challenges related to emissions reduction and operational efficiency. Traditional vessels, including those equipped with hydrofoil technology, encounter limitations in areas such as maintenance complexity, operational control, and user experience. Although hydrofoil technology offers benefits such as reduced water resistance, higher speeds, and improved energy efficiency, several critical areas still require innovation and improvement.

Key challenges include:

1. **Operational control and stability:** Hydrofoil vessels, particularly in variable sea conditions and during maneuvers, require sophisticated control systems to ensure stability, prevent capsizing, and optimize performance. Advanced control systems and automation solutions must be developed to enhance operational control and safety.

2. **User experience and accessibility:** Although hydrofoils are efficient, they can pose a steep learning curve for both operators and passengers. Simplifying user interfaces and integrating intuitive control systems are essential for achieving widespread adoption and enhancing the user experience.

3. **Integration with advancing technologies:** The integration of Automation 2.0 concepts and semantic technologies presents a significant opportunity to revolutionize hydrofoil systems. However, bridging the gap between traditional marine engineering practices and cutting-edge automation requires interdisciplinary collaboration and innovative approaches.

Addressing these challenges necessitates a comprehensive research and development effort focused on designing and building a platform to improve the understanding of hydrofoil dynamics, control systems, and automation integration. The objective of this project is to advance both theoretical knowledge and practical applications by developing a hydrofoil system.

2.2 Project Objectives

Hydrofoil control systems, particularly in the context of automation and autonomous navigation, have not been extensively explored in the existing literature. While there are commercial hydrofoil products available, academic research on these topics remains limited. This project aims to create a platform to enhance the understanding of hydrofoil operations and investigate their potential for automation, filling a gap in the current body of knowledge. The objectives of this report are as follows.

1. **Investigate Hydrofoil Design Principles:**
    - Conduct a comprehensive study of hydrofoil design principles, including foil shape, size, angle of attack, and material properties.
    - Develop a hydrofoil design for lift generation, reduced drag, and improved overall efficiency.
    - Utilize mathematical simulations and experimental testing to validate design iterations.
2. **Implement Control Algorithms and Hardware for Height and Pitch Control:**
    - Investigate sensor technologies such as accelerometers, gyroscopes, and altitude sensors for real-time feedback and adjustments.
    - Explore different types of controllers to achieve the required performance.
    - Develop and integrate control algorithms for precise height and pitch control of the hydrofoil.
    - Ensure stability, safety, and responsiveness of the control system under varying sea conditions and operational scenarios.

3. **Integrate Waypoint Navigation and Path Planning:**
    - Incorporate GPS and inertial navigation systems (INS) for accurate positioning and navigation.
    - Design and implement a waypoint navigation system for the autonomous operation of the hydrofoil.
4. **Integrate Communications and Reporting to a Base Station:**
    - Investigate different communication protocols for real-time data transmission.
    - Develop a method to communicate with a remote base station for monitoring and control.

By achieving these objectives, this research will demonstrate the viability, effectiveness, and potential of hydrofoil technology in revolutionizing maritime transportation, laying the groundwork for further development and commercial applications in the field.

3 Literature Review

3.1 Evolution and Principles of Hydrofoil Systems

The development of hydrofoil systems represents a significant milestone in maritime engineering, evolving from rudimentary concepts in the late 19th century to highly efficient, modern-day applications [5]. Early experiments notably those in 1906 by Enrico Forlanini, demonstrated the feasibility of using underwater wings to lift a boat above the water's surface, reducing drag and increasing speed [5]. However, it was not until post-WWII that hydrofiols gained more widespread attention, particularly in military and commercial sectors [5]. In 1950s, a notable achievement of 60 knots was attained by the U.S. Navy's hydrofoil ship, which solidified hydrofoils' potential in high-speed marine transport [5].

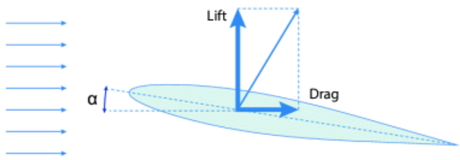

Figure 3.1: Wing Force Diagram[2].

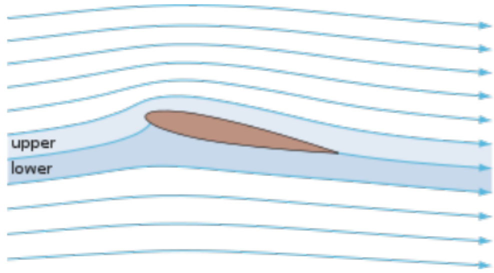

Figure 3.2: Airflow over the wing[2].

The fundamental principle behind hydrofiol technology lies in reducing hydrodynamic drag. When the vessel attains a certain speed, these hydrofoils generate lift force due to their aerodynamic design, much like an aeroplane's wings as shown in Figures 3.1 and 3.2 [2]. By lifting the hull out of the water as shown in Figure 3.3, hydrofoils minimize the contact area with the water, significantly reducing the resistance components that typically impede the vessel's movement through water, enabling hydrofoil-equipped vessels to travel at higher speeds with less fuel or electricity consumption than traditional vessels, a comparison in the difference of drag can be seen in Figure 3.4. This efficiency improvement is particularly advantageous for long-distance journeys or applications where speed and fuel economy are critical factors, such as in passenger ferry operations or recreational watercraft activities.

Figure 3.3: Candela C8 with hydrofoil wings[6].

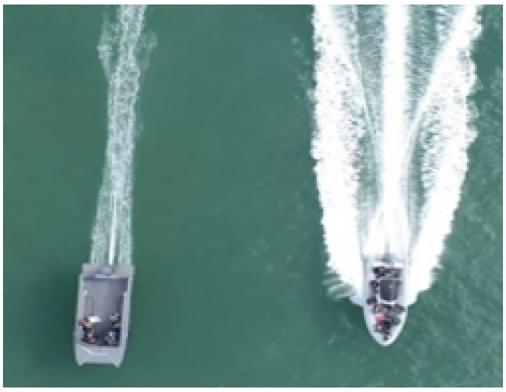

Figure 3.4: Comparison of wave trail between hydrofoil boat (left) and traditional boat (right) [7].

Modern advancements in fluid dynamics, materials science, and control systems have further improved the performance of hydrofoils, particularly in terms of their stability, efficiency, and safety. Hydrofoils now play dual roles, functioning not only as propulsion systems but also as control surfaces and structural elements in various marine applications [8]. Despite these advances, critical challenges remain. Early hydrofoils faced significant limitations in rough sea conditions, and even today, balancing speed, stability, and energy efficiency remains a complex task. This highlights the need for ongoing research into advanced control algorithms and automation systems to fully unlock the potential of hydrofoils.

Hydrofoils are primarily classified into two types: fully submerged and surface-piercing, these are depicted in Figure 3.5. Fully submerged hydrofoils operate entirely underwater, providing stability and consistent lift regardless of wave height or surface conditions. This design allows for significant drag reduction at high speeds, lifting the hull out of the water and improving efficiency [9]. It also offers flexibility in hull design. In contrast, surface-piercing hydrofoils feature V-shaped foils that extend partially above the water. While they can generate lift through hydrodynamic forces and air interaction, they are sensitive to turbulent water conditions. When waves are encountered, these foils can lose lift, resulting in instability [9]. However, one advantage of surface-piercing hydrofoils is that they typically do not require complex control systems, as they are inherently self-stabilising. Overall, the choice between these hydrofoil types depends on the specific application and operational environment, highlighting the importance of understanding their respective characteristics for effective design and performance.

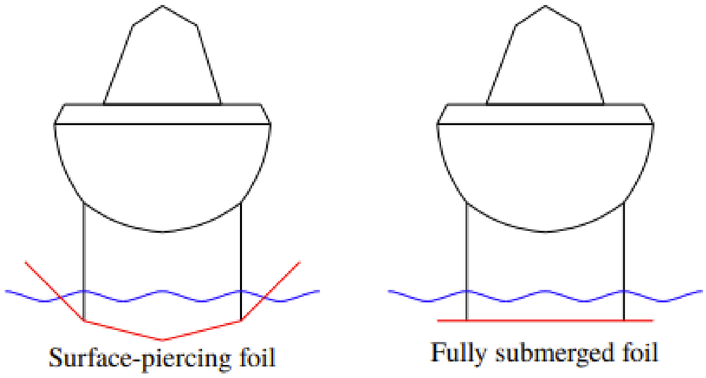

Figure 3.5: Different types of hydrofoils. Submerged (right) and Surface piercing (left).[10].

3.2 Relevance of Hydrofoils

Hydrofoils are highly relevant to the IMO's GHG strategy due to their potential to reduce fuel consumption and emissions in maritime transport. The IMO's GHG strategy, which aims to reduce total annual GHG emissions from international shipping by at least 50% by 2050 [1], focuses on improving energy efficiency and transitioning to low or zero-carbon technologies [1].

By reducing hydrodynamic drag, hydrofoils allow vessels to operate more efficiently, meaning less fuel is required to maintain higher speeds. This leads to lower $CO2$ emissions [11], aligning with the IMO's goals for reducing the environmental impact of shipping. In addition, hydrofoils can be effectively integrated with electric propulsion systems, reducing reliance on fossil fuels [11]. The development of automated or autonomous hydrofoil vessels could also contribute to more efficient voyage planning and speed optimization, which the IMO recognizes as key measures for reducing emissions in line with the Ship Energy Efficiency Management Plan (SEEMP) [1].

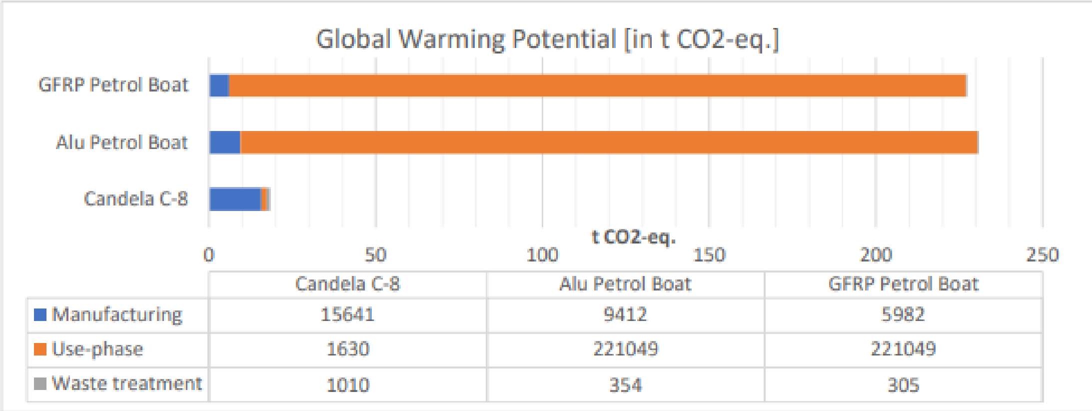

Figure 3.6: Total life cycle comparison for Global Warming Potential.[11].

Figure 3.6 compares the global warming potential of three different types of boats: a Candela C-8 hydrofoil boat, an aluminium petrol boat, and a glass-fibre-reinforced polymer (GFRP) petrol boat. It highlights the CO2-equivalent emissions from the different life stages of each boat: manufacturing, use-phase, and waste treatment.

The data shows that the hydrofoil boat has significantly lower emissions during the use phase compared to traditional petrol boats [11]. While the manufacturing emissions for the hydrofoil boat are higher, its overall environmental impact is much lower due to the minimal emissions during its operational life. In contrast, the petrol boats produce substantial emissions during the use phase, primarily due to fossil fuel consumption. This emphasizes the environmental benefits of hydrofoil electric boats in terms of reducing greenhouse gas emissions during their operational lifetime.

However, while hydrofoils contribute to reducing emissions, their widespread adoption is hindered by technological and economic factors. The cost of hydrofoil vessels remains higher than conventional ships, and the complexity of their control systems demands further innovation to make them more accessible to a broader range of maritime applications.

3.3 Technological Advancements and Applications

Candela Technology AB, based in Lidingö, Stockholm, is a leading manufacturer of electric boats and ferries known for their innovative use of hydrofoil technology [11]. Their latest advancements include the release of the Candela C-8 leisure boat and the upcoming launch of the P-12 ferry. These vessels are characterized by their combination of electric propulsion systems and hydrofoils, which significantly enhance efficiency and performance while minimizing environmental impact [11]. As stated in an IEEE magazine article [3], Candela's C-8 boat can cut energy consumption by 80% and has an extended range of 90km when compared to a similar traditional boat [3].

Similarly, the Renewable Energy Vehicle Project (REV) Team at the University of Western Australia (UWA) achieved a remarkable feat by converting a 2008 sea-doo into a fully electric PWC named 'REVSki' as shown in Figure 3.7 [12]. This e-PWC can accommodate two passengers, offers a range of 25 minutes, and can reach a top speed of 41km/h, providing performance comparable to traditional PWCs without the drawbacks of noise and pollution. Despite this success, a significant portion of the PWC's energy is wasted in overcoming waves, limiting its range. To address this energy inefficiency, the REV team pioneered the world's first electric hydrofoil PWC in 2019 [12]. This hydrofoil-equipped PWC delivers a much quieter, more energy-efficient, and emission-free performance. By raising the PWC above the water surface using hydrofoils the energy expenditure in crashing into waves is minimised, allowing for a range of 30 minutes with just 2kWh of energy [12]. However, while the development of electric hydrofoil PWCs represents a significant advancement, there are challenges inhibiting their widespread adoption and convenient usage. A major focus lies on the rider's ability to both elevate and bank the hydrofoil ski effectively. Therefore, there is a demand for the automation of this process, and to streamline the operation of hydrofoil skis to make them more accessible to a broader range of users.

Figure 3.7: UWA REV Waveflyer - Hydrofoil JetSki.[12].

This reflects the current trend in our industry towards adopting automation 2.0 solutions. It refers to a significant evolution in computer-based automation systems, akin to the transition from electromechanical relays to programmable logic controllers in the mid-1960s [13]. This new phase involves devices and machines capable of autonomously discovering and collaborating towards common goals without prior knowledge of each other's type. It relies on dynamic architectures for autonomous reconfiguration of hardware and software architectures, employing software that intelligently utilises web services to build adaptive systems [13]. These systems exhibit emergent behaviour geared towards user goals while maintaining a chaotic yet structured nature [13].

Likewise, the maritime industry is making significant progress towards automation, with a key focus on autonomous marine vehicles and broader technological integration [14]. Automation efforts are primarily aimed at enhancing safety, efficiency, and sustainability. Key technologies being explored include remote-controlled vessels, fully autonomous ships, and cyber-physical systems that streamline navigation, communication, and cargo management [14]. These advancements are part of a broader trend towards the use of AI, machine learning, and robotics in maritime operations.

In terms of the levels of autonomy, there are several stages:

- **Manual Control:** No automation; human operators control all functions [14].
- **Decision Support:** Automation assists with decision-making but requires human input [14].
- **Partial Autonomy:** Vessels can perform some tasks independently but still rely on human oversight [14].
- **Full Autonomy:** Ships can operate entirely without human intervention [14].

Current automation efforts are aimed at achieving greater operational flexibility, reducing human error, and enabling more efficient resource management. The long-term goal is to develop fully autonomous ships that can navigate complex maritime environments while ensuring safety and regulatory compliance [14]. This transition is expected to revolutionize shipping logistics, reduce carbon footprints, and optimize maritime operations globally. As of now, several pilot projects are underway, exploring these technologies, especially in controlled environments such as ports and harbours [14].

Figure 3.8: Autonomous ferry "Utrecht" Developed by Rolls Royce [14].

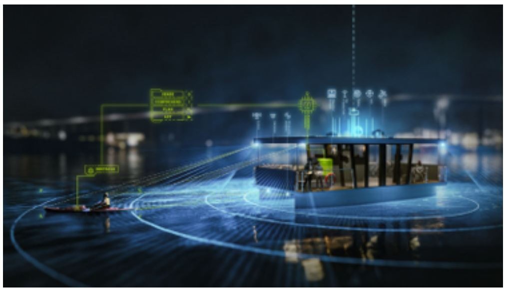

Figure 3.9: Zeabuz Autonomous Electric Ferry [15].

Rolls-Royce's Utrecht project shown in Figure 3.8 focuses on autonomous shipping through its *Ship Intelligence* initiative [14]. It employs AI-driven navigation, remote operation centers, and sensor fusion to enhance situational awareness and automate docking processes [14]. The system aims to reduce crew size and optimize efficiency in maritime operations[14]. Another example is Zeabuz, based in Stockholm, specializes in fully autonomous electric ferries as depicted in Figure 3.9 for urban water transport [15]. Their vessels use advanced sensors and AI for collision avoidance and navigation in busy waterways [15]. Zeabuz's goal is to revolutionize short-distance passenger transport with zero-emission, crewless ferries, enhancing sustainability and operational flexibility [15].

3.4 Control and Automation Systems in Hydrofoils

Traditional ships have implemented automation systems to enhance navigation, collision avoidance, and vessel management using technologies like AI and remote control systems [14]. However, when it comes to hydrofoils, automation remains largely unexplored. There is a noticeable gap in the research regarding fully autonomous hydrofoils, even though the control algorithms and automation theories used for traditional ships could be applied to these vessels.

Control systems are integral to the operation of autonomous and semi-autonomous vessels. Their purpose is to guide the system to a desired state by utilizing feedback from onboard sensors. A typical control system involves measuring the vessel's current state (e.g., speed, direction, and altitude above the water), comparing it to a desired target state, and adjusting actuators or control surfaces to minimize any deviation. In hydrofoils, these adjustments are especially important since stability while foiling is important for efficiency and safety. Control systems can be broadly categorized as manual, mechanical, or electronic/software-based [16]. While manual and mechanical systems are used in basic applications, electronic and software control systems are essential for modern, automated hydrofoil designs [16]. Some control systems that have been applied to hydrofoils are Proportional-Integral-Derivative (PID) controllers, Linear Quadratic Regulators (LQR), and Sliding Mode Controllers (SMC) [17]. Each of these systems seeks to achieve stability and performance by responding to disturbances in the vessel's dynamics.

For instance, PID controllers use feedback from sensors (such as accelerometers or gyroscopes) to calculate an error value, which is used to adjust the hydrofoil's control surfaces like the ailerons, wings, and rudder [17]. This system continuously adjusts based on proportional, integral, and derivative responses to minimize error over time. LQR and SMC go beyond PID, providing more advanced control strategies that are designed to handle non-linearities and reduce sensitivity to disturbances such as waves or wind gusts [17].

Control surfaces on hydrofoils play a critical role in maintaining the boat's stability and maneuverability. Ailerons and hydrofoil wings are used to adjust the vessel's pitch, roll, and height above the water, while the rudder controls yaw. These surfaces must respond quickly to inputs from the control system to ensure that the vessel remains stable, particularly at high speeds when hydrofoils are lifted out of the water. The control system's ability to manage these surfaces and compensate for disturbances (such as wave motion) is key to successful autonomous operation [16]. Characteristics like responsiveness, range of motion, and the aerodynamic/hydrodynamic properties of the control surfaces must be carefully considered in the system's design [16].

From a critical review of existing literature, it can be seen that the development of fully autonomous hydrofoils is still in its infancy. Key research areas include improving control algorithms for maintaining stability in varying sea conditions, reducing sensitivity to disturbances, and ensuring fail-safe operation. Advances in machine learning and AI offer the potential for self-optimizing hydrofoil systems that can adapt to real-time environmental changes, further enhancing performance.

4 Design Process

The scope of this report centres around the design and implementation of hydrofoil wings, the development of a control system to stabilize the vessel in one axis, the creation of waypoint navigation capabilities, and the integration of communication systems and sensors. The focus of the design process was to ensure a balance between performance, stability, and operational control. Therefore, this section will explore the critical considerations and methodologies applied during the design phase, detailing how the project objectives were systematically approached and achieved.

4.1 Inspirations

The design process for our hydrofoil system was largely inspired by the Candela C-8, which provided a practical concept and helped shape the visual direction of our design. Much of the knowledge and insights came from discussions around boat-building and hydrofoil systems, supported by expert input from Pierre-Louis Constant. The REV research group's past experiences, specifically their work on the REV hydrofoil, heavily informed key design considerations and assumptions. Additionally, practical advice on construction and manufacturing was gathered from individuals with hands-on experience in building similar marine vessels, helping us anticipate potential challenges and refine our approach.

4.2 Ideation and Implementation

4.2.1 Limitations and Assumptions

The conceptualization of the hydrofoil system required several assumptions and constraints to ensure that the design was both feasible and functional within the project's scope. Key limitations included:

- **Budget Constraint:** The project was limited to a budget of $1000, which necessitated careful material selection and component sourcing. Every design decision was made with cost-effectiveness in mind while ensuring the system's performance would not be compromised.

- **Speed Limitation:** Based on previous experience with similar equipment, the maximum operating speed of the hydrofoil was set at 20 km/h. This speed limit was critical for determining the design of the hydrofoil wings and the choice of materials, ensuring that the system would operate safely and efficiently within this range.
- **Size Restriction:** The system was constrained to a length of 1 meter and a mass of approximately 10 kilograms. This size was chosen as it provided a balance between ease of fabrication and maintaining sufficient hydrodynamic performance. Larger sizes would introduce logistical challenges, while smaller sizes would limit the precision and robustness of testing.

4.2.2 Mathematical Simulation

The design process was supported by a mathematical simulation to theoretically test and refine the hydrofoil wing design. By using well-established lift and drag equations, the simulation helped ensure that the required lift would be generated, validating the hydrofoil's capability for the intended operating conditions [18][19].

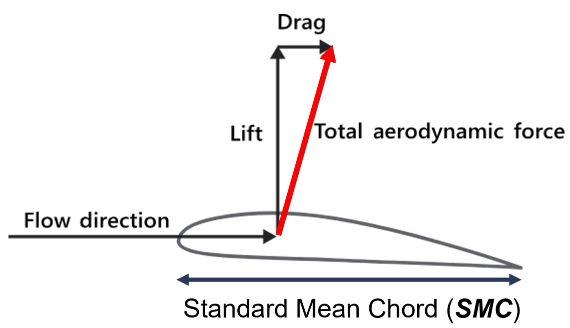

Figure 4.1: Forces Diagram of a Wing.

The lift and drag forces acting on a hydrofoil wing can be shown by the Figure 4.1. The forces are calculated using the following equations:

$$L = \frac{1}{2} C_L \rho V^2 A \tag{1}$$

$$D = \frac{1}{2} C_D \rho V^2 A \tag{2}$$

$$AR = \frac{b^2}{A} = \frac{b}{SMC} \tag{3}$$

Where:

- L is the lift force.
- D is the drag force.
- C_L is the lift coefficient.
- ρ is the fluid density.
- V is the relative velocity of the wing in the fluid.
- A is the reference area of the wing.
- AR is the aspect ratio of the wing.
- b is the wingspan.
- SMC is the standard mean chord length.

To find the reference area of the wing, the calculation was simplified by treating the wing as a rectangular prism with a cross-section area as shown in Figure 4.2.

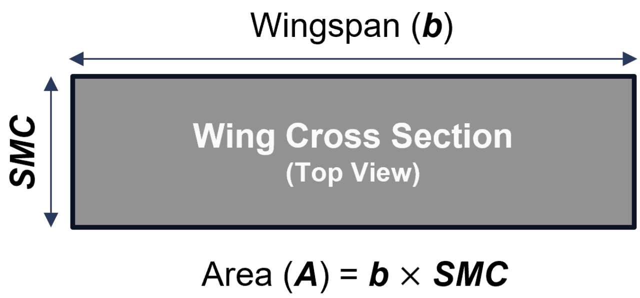

Figure 4.2: Cross-section area of a wing.

The mathematical simulation of the hydrofoil design helped in understanding the aerodynamic forces acting on the wings, namely lift (L) and drag (D). These forces are critical for ensuring that the hydrofoil can provide sufficient lift to raise the hull out of the water while minimizing drag to maintain efficiency at high speeds. The equations used in the simulation define how lift and drag are influenced by various parameters like fluid density (ρ), velocity (V), wing area (A), and the lift/drag coefficients (C_L and C_D).

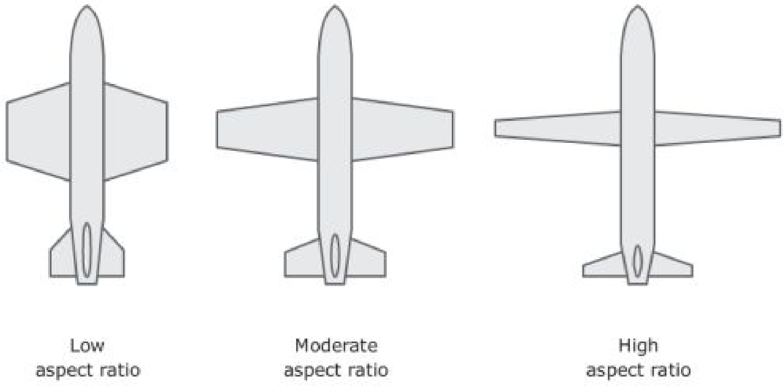

Figure 4.3: Comparison of different aspect ratios[20].

One of the key factors in wing performance is the **aspect ratio** (AR), which is the ratio of the wingspan (b) to the mean chord length (SMC) [20]. A high aspect ratio means the wing is long and narrow, while a low aspect ratio indicates a short and wide wing, which can be seen in Figure 4.3. Aspect ratio affects the aerodynamic efficiency of the wing:

- **High Aspect Ratio:** Wings with a high aspect ratio generate less induced drag (vortex drag at the wingtips), which makes them more efficient for producing lift [20]. This is beneficial in applications requiring endurance and smooth, sustained lift, such as in gliders or hydrofoils. High AR wings are often used in hydrofoils to maintain efficient lift with low drag at high speeds.

- **Low Aspect Ratio:** Wings with a low aspect ratio are typically stronger and more maneuverable but create more induced drag [20]. They are better suited for situations requiring high maneuverability but are less efficient in terms of lift-to-drag performance.

In addition to optimizing the lift and drag characteristics, the **torque and moments** produced by the wings must be considered, a simple force and moment diagram of the hydrofoil is shown in Figure 4.4. A hydrofoil typically has two main wings: a front wing and a rear (or stabilizer) wing [17]. The front wing is positioned forward of the centre of gravity (CoG), generating lift that helps raise the vessel. Meanwhile, the rear wing, located behind the CoG, balances the moment generated by the front wing. These wings produce opposing torques, and their careful balancing is required to maintain the hydrofoil's pitch stability [18]. If the moments are unbalanced, the hydrofoil may pitch up or down uncontrollably. Proper wing placement and control surfaces ensure smooth operation.

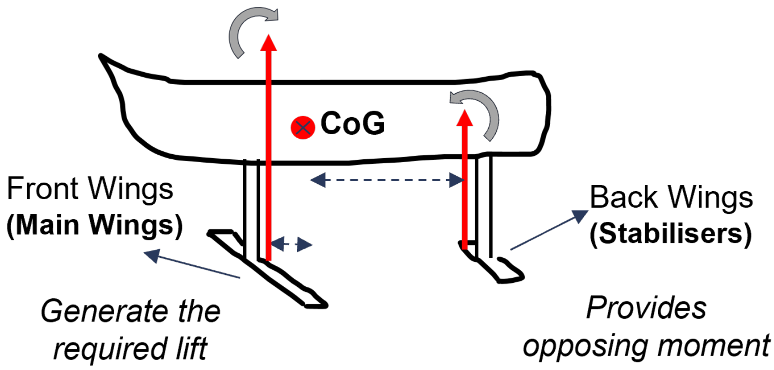

Figure 4.4: Comparison of different aspect ratios.

The shape or **airfoil profile** of the hydrofoil wings also plays a significant role in performance [10]. The same wing profiles used in aeroplanes, such as NACA airfoils [21], can be applied to hydrofoils. These profiles help in determining the amount of lift and drag the wing will generate at different speeds and angles of attack (AoA) [21].

The AoA refers to the angle between the oncoming flow of fluid (relative flow) and the chord line of a wing or hydrofoil [21] as depicted in Figure 4.5. The chord line is an imaginary straight line connecting the leading and trailing edges of the wing. In wing development, the AoA is used to optimize the lift-to-drag ratio. As the angle of attack increases, the lift generated by the wing increases up to a certain point (the critical AoA). Beyond this critical angle, the wing experiences stall a condition where the airflow separates from the wing's surface, causing a rapid drop in lift and a sharp increase in drag [22]. For hydrofoils, designing wings with the proper AoA ensures that they generate enough lift for stability without stalling [22].

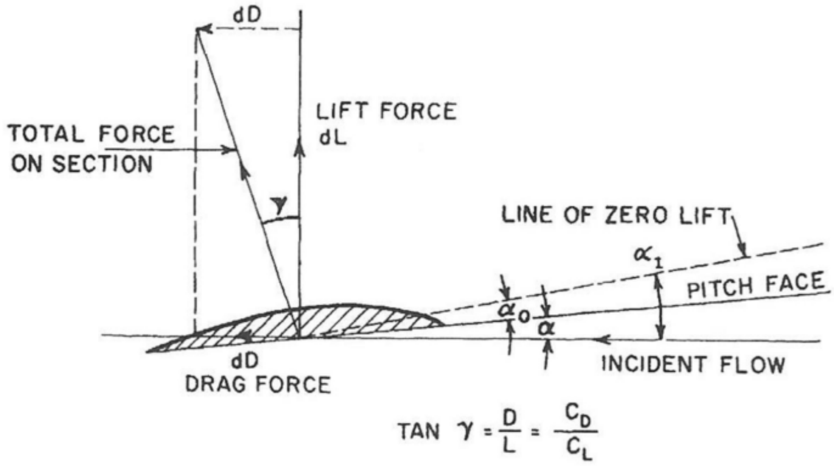

Figure 4.5: Diagram of Angle of Attack (α). [22].

Furthermore, selecting an appropriate airfoil is important for balancing lift, drag, and stability. For instance, a thicker airfoil profile can generate more lift at lower speeds, which is beneficial for the take-off phase. Conversely, thinner profiles are more suitable for high-speed operations, as they reduce drag but may provide less lift at lower speeds [21]. The trade-off between lift and drag, and the construction complexity of the wing, must be considered during the design phase. Different airfoils will also affect the hydrofoil's ability to operate efficiently across different speed ranges.

By integrating theoretical lift/drag equations and torque balance considerations, this design process ensures efficient and stable hydrofoil operation. As the research doesn't aim to optimize the hydrofoils themselves, a mathematical simulation suffices to achieve the necessary hydrofoiling operation, eliminating the need for complex simulations like Computational Fluid Dynamics (CFD).

4.2.3 Materials and Modularity

When designing and implementing hydrofoils, the selection of materials plays a pivotal role in influencing not only the structural performance but also the overall project costs and manufacturing processes. The choice of materials affects the weight, strength, and durability of the hydrofoil, which in turn impacts the hydrodynamic efficiency, handling, and operational lifespan [22]. Additionally, different materials vary significantly in terms of cost, ease of fabrication, and environmental impact, making it essential to balance performance requirements with budget constraints. High-performance materials often come with a higher price tag and may require specialized manufacturing techniques, adding complexity to the design process. Conversely, opting for cheaper materials might compromise performance or longevity, especially in the harsh marine environment. Thus, material selection becomes a key trade-off between performance, cost, and ease of manufacturing.

Another aspect considered during the design process was modularity. Modularity is equally important in hydrofoil design as it enhances flexibility, scalability, and ease of maintenance. A modular design approach allows different components of the hydrofoil—such as wings, struts, and control systems—to be developed, tested, and replaced independently, without the need for redesigning the entire system. This simplifies not only the prototyping phase but also future upgrades, repairs, and part replacements. Moreover, a modular system offers significant long-term cost savings, as individual components can be swapped out or enhanced as needed, rather than investing in a complete replacement. This approach ultimately supports better adaptability and life cycle management, making it ideal for experimental research projects.

4.3 Stabilising Control Systems

The **Control Phase** is crucial in the operation of the hydrofoil system because once the boat reaches the hydrofoiling state, it enters a naturally *unstable condition* [10]. At this point, the boat is lifted above the water by its hydrofoil wings, drastically reducing drag but making it more susceptible to external forces like wind, waves, and changes in speed. This necessitates a **stabilization algorithm** to maintain balance and ensure smooth operation [17].

4.3.1 Importance of Control Systems

Control systems serve the primary function of managing and regulating the behaviour of a system, ensuring it performs as desired. In the context of hydrofoils, control systems are responsible for maintaining stable flight above water, adjusting the angles of wings, and responding to external forces like waves or wind. Without a control system, the hydrofoil would struggle to maintain the desired altitude or heading, leading to unstable or inefficient operation.

The importance of a control system also lies in its ability to provide feedback. By constantly measuring variables such as speed, position, and angle of attack using sensors, the control system can adjust the hydrofoil's surfaces—such as wings or rudders—to correct any deviations from the intended trajectory. This feedback loop ensures that the hydrofoil can adapt to changing conditions in real time, optimizing performance and maintaining safety.

To effectively control the dynamic behaviour of a hydrofoil, one of the most commonly used control techniques is the Proportional-Integral-Derivative (PID) controller [23]. A PID controller continuously calculates the error between a desired setpoint and the actual output, using this error to adjust the control input in real time [23]. A block diagram of how the controller works is shown in Figure 4.6. The three components — Proportional, Integral, and Derivative — each play a critical role in ensuring stability and accuracy.

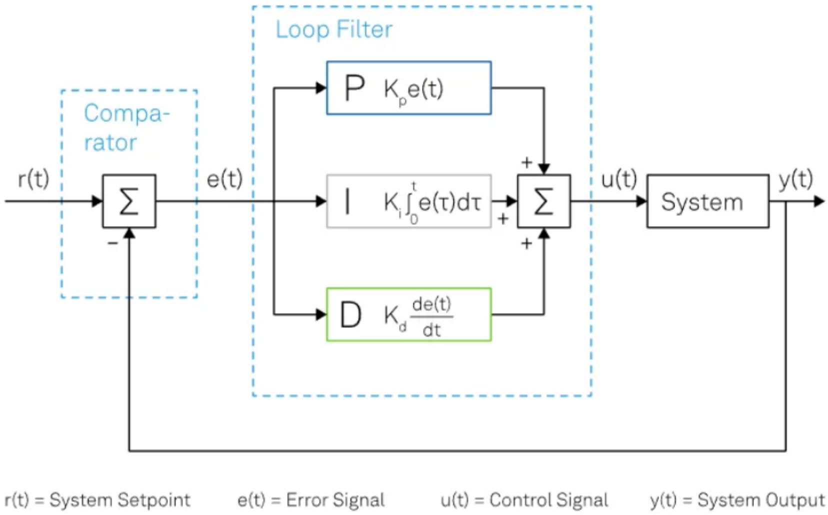

Figure 4.6: Representation of a general PID control loop in general form. [23].

1. **Proportional (P):** The proportional term produces an output that is proportional to the current error. If the boat deviates from its desired height or orientation, the proportional term will act to reduce that deviation. However, proportional control alone can lead to steady-state errors, where the system never quite reaches the target [23].

2. **Integral (I):** The integral term sums up past errors over time and acts to eliminate the cumulative error. This is particularly useful in correcting any steady-state error left by the proportional term [23].

3. **Derivative (D):** The derivative term predicts future errors by calculating the rate of change of the error. It helps to dampen the response and smooth out overshoots or oscillations in the system's performance, making the control more stable [23].

A cascade controller, often used in conjunction with a PID controller, is an advanced control strategy where multiple control loops are implemented in a hierarchical structure [24] as shown in Figure 4.7. In this setup, the primary control loop is responsible for high-level control objectives, such as maintaining the hydrofoil's overall direction or altitude.

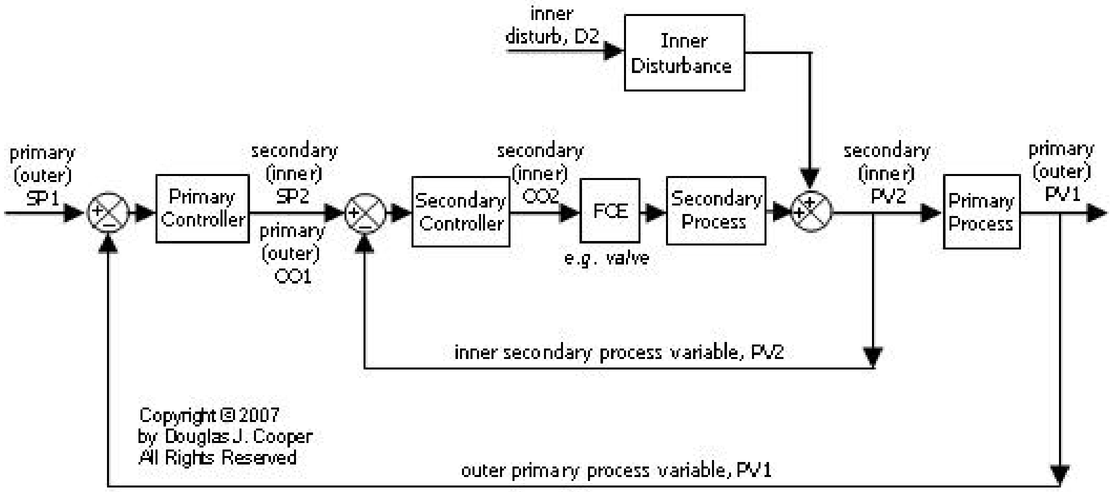

Figure 4.7: Representation of a general Cascade Controller. [24].

This loop sends setpoints to a secondary control loop, which deals with more immediate, lower-level dynamics, such as adjusting the angle of the hydrofoil's wings or rudder to respond to rapid changes. By splitting the control tasks across multiple loops, cascade control improves both stability and responsiveness.

4.3.2 Defining the state of a Hydrofoil

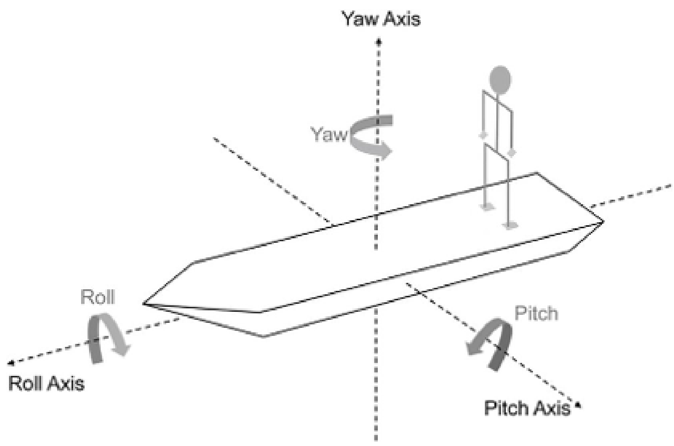

Figure 4.8: Roll, Pitch and Yaw axis of a boat. [25].

As seen in Figure 4.8 the boat's movement is governed by three key rotational axes:

1. **Roll:** The boat's side-to-side tilting motion [25]. In a hydrofoil system, roll stability is crucial to prevent the boat from tipping sideways during operation.
2. **Pitch:** The up-and-down tilting motion of the boat's bow (front) and stern (back) [25]. Pitch directly affects the boat's height above the water surface. For a hydrofoil system, pitch control is essential to maintaining the correct height, ensuring the boat stays above water without sinking or becoming too elevated [17].
3. **Yaw:** The left-to-right rotation around the boat's vertical axis [25]. Yaw control is necessary for steering and directional stability.

In the context of the hydrofoil, precise control over **pitch** and **roll** is critical for maintaining a stable height above the water, while **yaw** is less involved in the stabilization of height but is important for navigation.

For a hydrofoil to operate effectively, it must maintain a certain height above the water. The *height* of the boat is influenced by the *pitch*, which controls the angle at which the hydrofoil wings engage the water [17]. If the pitch increases, the boat will rise higher; if the pitch decreases, the boat will lower. When the boat pitches upwards, the angle of attack of the hydrofoil wings increases, leading to more lift and causing the boat to rise. Conversely, if the pitch decreases, the lift is reduced, and the boat lowers itself closer to the water's surface. Maintaining a steady height is crucial to prevent the boat from bouncing in and out of the water, which would destabilize it and reduce efficiency [17].

4.3.3 Sensors Required for Feedback

Accurate real-time data is essential for maintaining the stability of the hydrofoil system. To achieve this, two key sensors were implemented: an **Inertial Measurement Unit (IMU)** to provide information about the boat's orientation, and a **height sensor** to measure the boat's height above the water surface.

An **IMU** is a device that measures and reports on a body's specific force, angular velocity, and the orientation of the object in space. IMUs are commonly used in a variety of control systems, including drones and robotics, due to their ability to provide crucial data for stabilizing platforms. For this project, the IMU was particularly useful for capturing pitch, which is critical in maintaining the boat's height and balance during hydrofoiling.

To maintain the correct height above the water's surface, a height sensor was implemented. The primary purpose of the height sensor was to provide reliable feedback for controlling the boat's pitch, ensuring it remained within the desired height range above the water. To ensure robustness in varying conditions, sensor redundancy principles were applied, meaning multiple sensors or measurement methods were evaluated. This allowed for cross-checking data to minimize errors due to sensor failure or environmental factors.

Moreover, sensor accuracy, waterproofing, and longevity were critical factors in deciding the final sensor choice. The sensor had to be reliable under different water conditions, resilient to the marine environment, and capable of providing precise data. Ensuring the sensor's durability and accuracy was essential for maintaining long-term system performance and avoiding potential malfunctions that could affect stability. These factors collectively influenced the selection of the most appropriate sensor option for this hydrofoil application.

4.4 Autonomous Driving and Navigation

Autonomous driving and navigation refer to a system where a vehicle, in this case, a hydrofoil boat, operates independently by following an algorithm designed to guide it along a predetermined path. The algorithm continuously monitors the boat's current position, direction, and environmental conditions, sending instructions to the control system to adjust its state and maintain the desired setpoints. In this project, a basic autonomous navigation system was developed, focusing on waypoint driving.

Research in the maritime industry has already demonstrated successful implementation of GPS-based navigation in autonomous boats. GPS driving was chosen as the starting point for this project due to its simplicity and proven reliability, offering a solid foundation for future development. By implementing basic GPS waypoint driving, it was possible to test the control system's ability to achieve desired states and reach set goal points. This forms a crucial step in verifying the boat's overall performance and provides a base upon which more advanced autonomy techniques can be built and explored in future iterations.

4.4.1 Waypoint Navigation System

Waypoint navigation involves guiding a vehicle or vessel to a series of predetermined geographical locations (waypoints). The vessel constantly updates its position via GPS and adjusts its direction to travel towards the next waypoint.

- **Waypoints:** These are geographical coordinates (latitude, longitude) stored in the system's memory, marking the path the boat needs to follow.
- **Navigation Process:** At each point, the boat calculates the bearing (direction) and distance to the next waypoint. Based on these calculations, the control system adjusts the boat's heading to follow the optimal path toward the target location.

This navigation method is effective for long-distance travel, allowing the hydrofoil to travel from one point to another accurately, regardless of external disturbances like wind or currents.

4.4.2 GPS Navigation: How It Works

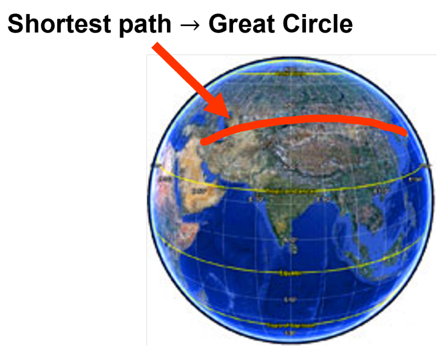

Figure 4.9: The shortest great circle path [26].

To guide the boat, **GPS (Global Positioning System)** data was utilized, which provided real-time position updates. GPS navigation calculates the shortest path between two points on the Earth's surface, known as the *great circle path* [26] as depicted in Figure 4.9. The main steps involved in this process include:

1. **Traveling Between Two Points:** The system calculates the great circle distance (the shortest distance between two points on a sphere) and uses this to navigate.

2. **Changing Bearings on a Great Circle Path:** As the boat moves along the great circle, the bearing (direction to travel) constantly changes due to the curvature of the Earth. This introduces complexity in the heading control, as the boat must continuously adjust its heading to maintain the shortest path [26].

3. **Bearing Calculation Using the Azimuth Equation:** To account for this curvature and ensure the boat follows the correct path, the azimuth equation (4) [26] was used, which calculates the bearing angle between two points on the Earth's surface. This equation gives the initial heading to follow at the start of the journey, but as the boat progresses, the bearing is recalculated dynamically based on its updated position.

The **Azimuth Equation** is essential for calculating the bearing between two points on the Earth's surface. It helps guide the boat's navigation by constantly adjusting its direction to stay on course.

$$\theta = \text{atan2}\left(\sin(\Delta\lambda) \cdot \cos(\phi_2), \cos(\phi_1) \cdot \sin(\phi_2) - \sin(\phi_1) \cdot \cos(\phi_2) \cdot \cos(\Delta\lambda)\right) \quad (4)$$

Where:

- θ is the azimuth or bearing angle, giving the direction from the starting point to the goal point.
- ϕ_1, ϕ_2 represent the latitudes of the starting and goal points, respectively.
- $\Delta\lambda$ is the difference in longitudes between the two points.

This equation is particularly useful because it accounts for the Earth's curvature and ensures that the boat follows the shortest possible path (a great circle) between two points. The *atan2* function is used here to handle the quadrants and return the correct bearing angle, ensuring accurate directional adjustments even when crossing hemispheres.

For long-distance navigation, the main objective was to ensure the boat stayed on course and accurately reached its final waypoint. To achieve this, both distance calculations and heading control need to be employed.

The straight-line distance between the boat's current position and the goal was determined using the **Haversine equation** (5) [26], which accounts for the Earth's curvature. This is essential for calculating the shortest path (a great circle distance) between two points on the Earth's surface.

$$d = 2r \cdot \text{asin}\left(\sqrt{\sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_1) \cdot \cos(\phi_2) \cdot \sin^2\left(\frac{\Delta\lambda}{2}\right)}\right) \quad (5)$$

Where:

- d is the distance between two points along the surface of the Earth.
- r is the Earth's radius, approximately 6,371 kilometers.

- $\Delta\phi$ is the difference in latitudes between the two points.
- $\Delta\lambda$ is the difference in longitudes between the two points.
- ϕ_1, ϕ_2 represent the latitudes of the starting and goal points, respectively.

This equation allowed continuous monitoring of the distance remaining to the target waypoint. By calculating this distance, the boat's control system could adjust its course as needed to ensure it stayed on the correct path. The Haversine formula is critical for long-distance navigation as it accurately considers the Earth's spherical shape, thus helping verify if the boat's trajectory remained optimal.

4.4.3 Integrating GPS Sensor

A GPS sensor is an essential component for navigation, providing the precise location of the boat by determining its latitude, longitude, and altitude using satellite signals. The GPS sensor communicates with a constellation of satellites orbiting Earth to triangulate the receiver's position through time-stamped signals. The accuracy of GPS can be further improved by using a Differential GPS (DGPS) system, which applies correction data from a network of fixed ground-based reference stations.

The GPS sensor transmits this navigation data in the form of *NMEA (National Marine Electronics Association)* sentences, which are standardized text strings containing various pieces of information such as position, time, velocity, and satellite information. These sentences are regularly output by the GPS sensor and are used for real-time navigation and position tracking.

Two types of NMEA sentences are primarily used: **GPGGA** and **GPRMC**, which provide critical navigation data for decision-making.

The GPGGA (Global Positioning System Fix Data) sentence provides essential information about the GPS fix, including:

- Latitude and longitude of the current position.
- Time of position fix in UTC (Universal Coordinated Time).

- Number of satellites being tracked, which can help gauge the accuracy of the fix.
- Altitude and the quality of the GPS fix.

This sentence is useful for understanding the quality of the GPS data and ensuring that the boat's current position is accurately tracked.

The GPRMC (Recommended Minimum Specific GPS Data) sentence contains:

- Position information (latitude and longitude).
- Time and date.
- Speed over ground.
- Heading or course over ground.

This sentence provides essential data for navigation, particularly when determining the boat's current speed and heading. It allows the control system to adjust the boat's course accordingly to ensure it stays on the desired path.

By parsing these NMEA sentences, the navigation system receives a continuous stream of position and motion data, enabling the boat to follow its planned route and respond to changes in its environment.

4.5 Communications

Effective communication between the hydrofoil boat's onboard system and external devices was essential to monitor the boat's state, sensor data, and controller status in real-time. Without proper communication, it would be impossible to observe the boat's internal dynamics and make necessary adjustments. Furthermore, this communication is crucial in understanding the internal processes of the boat, monitoring its operational parameters, and providing a means to control and manage data stored onboard.

4.5.1 Processing Architecture

The system's processing architecture is designed around a low-cost microcontroller, which is an economical choice considering budget limitations. The microcontroller plays a key role in managing sensor data, communication, and control algorithms.

When selecting the microcontroller, several factors were taken into account:

- **Number of I/O pins**: The microcontroller needs enough input/output pins to handle all the sensor inputs, actuator outputs, and communication interfaces.
- **Communication protocols**: It must support a variety of communication protocols such as UART, I2C, and SPI, ensuring compatibility with the boat's onboard sensors and actuators.
- **Data storage**: The microcontroller should be capable of storing data collected from sensors or relayed through communication modules for real-time analysis or future reference.
- **Additional functionality**: Features like built-in wireless communication (e.g., Wi-Fi or Bluetooth) enhance connectivity without requiring external modules.
- **Processing speed**: The microcontroller needs sufficient processing power to handle real-time control loops and data processing.

4.5.2 Internal Communications

Internal communication refers to the data exchange between sensors, controllers, and actuators. This communication ensures real-time feedback for adjusting the control surfaces and maintaining stability, which is crucial for hydrofoiling. Various communication protocols were evaluated, each offering different advantages in terms of speed, complexity, and wiring requirements.

1. **I2C (Inter-Integrated Circuit):**

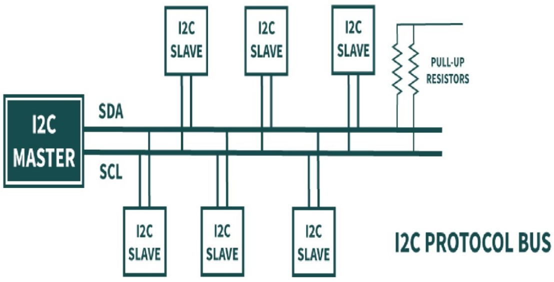

Figure 4.10: I2C protocol wiring diagram. [27].

I2C is a simple two-wire communication protocol, using SCL (Serial Clock Line) and SDA (Serial Data Line), where multiple devices can share the same bus [27] as shown in Figure 4.10. It is commonly used in applications requiring low-speed communication between devices such as sensors or microcontrollers [27].

- **Advantages**: I2C is easy to implement and minimizes the number of physical connections, making it ideal for situations where simplicity is prioritized, and the data transfer speed is not a critical factor.

- **Disadvantages**: One downside of I2C is its relatively slower data rate (typically up to 400 kbps) [27], which can lead to delays in high-speed control applications like hydrofoiling, where fast response times are essential to maintain stability.

2. **SPI (Serial Peripheral Interface):**

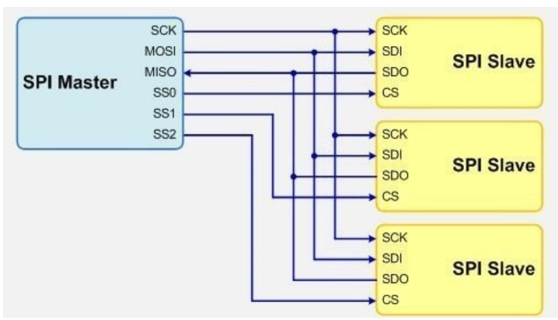

Figure 4.11: SPI protocol wiring diagram. [28].

SPI is a four-wire communication protocol using MISO (Master In Slave Out), MOSI (Master Out Slave In), SCK (Serial Clock), and SS (Slave Select) [28] as shown in Figure 4.11. It provides high-speed data transfer and precise timing control, making it suitable for time-critical applications [28].

- **Advantages**: SPI offers a much higher data rate (up to several Mbps) compared to I2C, making it a better choice for real-time control systems [28]. It also allows better synchronization between devices, which is crucial for maintaining responsive control over the boat's pitch and roll in dynamic environments.
- **Disadvantages**: The complexity of SPI is higher than I2C, requiring more physical connections and a more involved configuration process.

3. **UART (Universal Asynchronous Receiver-Transmitter):**

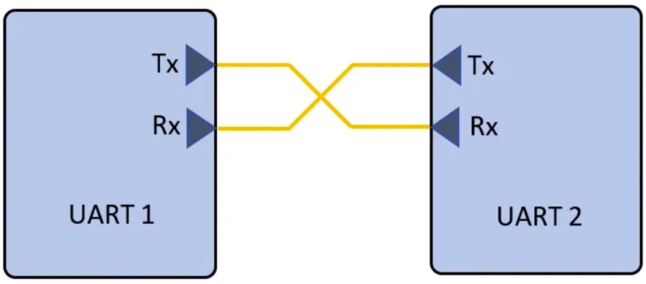

Figure 4.12: UART protocol wiring diagram. [29].

UART is a widely used serial communication protocol for sending data between devices. Unlike SPI and I2C, UART is asynchronous, meaning it does not use a clock signal to synchronize communication [29], which can be seen from Figure 4.12.

- **Advantages**: UART is simple to implement and is often used for longer-distance communication compared to SPI and I2C. It supports full-duplex communication (data can be transmitted and received simultaneously) and is typically used for communication with external devices such as GPS modules or wireless communication modules [29].

- **Disadvantages**: Because UART operates asynchronously, it is generally slower than SPI and does not guarantee data timing as precisely, which can be an issue in real-time control scenarios [29].

4.5.3 Remote Communications

Remote communication allows for the external monitoring and control of the boat's state. It enables external devices or operators to remotely track the boat's position, speed, and other parameters while also providing the capability to control or adjust the data stored on the boat. This is essential for making real-time adjustments, diagnosing issues, and ensuring the boat remains on course or reacts to environmental changes.

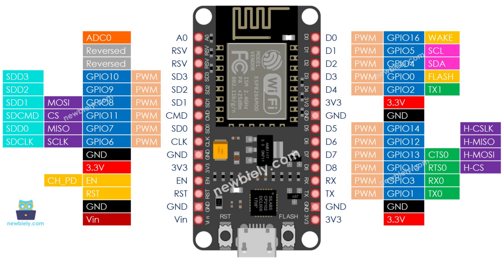

Figure 4.13: ESP8266 Module Pinout[30].

Figure 4.14: HC-12 Radio Module [31].

Two primary options were investigated for wireless communication:

1. **HC-12 RF Transceiver Module** (Figure 4.14)
2. **ESP8266 Wi-Fi Module** (Figure 4.13)

Both of these modules provide different communication capabilities, and their performance needed to be evaluated based on various technical considerations.

The HC-12 RF transceiver is a low-cost, long-range wireless communication module that operates in the **433 MHz** frequency band. It is designed for half-duplex communication, meaning it can either send or receive data, but not both simultaneously.

How the HC-12 Works:

- The HC-12 communicates with the microcontroller via a serial UART interface. The microcontroller sends and receives data to and from the HC-12 through its TX/RX pins [31].
- The module uses amplitude shift keying (ASK) or frequency shift keying (FSK) modulation to transmit data wirelessly over long distances (up to 1.8 km in line of sight) [31].

Advantages:

- Long Range: The HC-12 can transmit data over distances up to 1.8 km, making it suitable for outdoor applications like hydrofoiling, where the boat may be far from the operator.
- Low Power Consumption: Since the HC-12 operates in the sub-1GHz range, it consumes less power compared to Wi-Fi-based solutions.

Disadvantages:

- Lower Data Rate: The data transmission rate of the HC-12 is slower compared to Wi-Fi modules, with a maximum baud rate of around 115,200 bps.
- Half-Duplex Communication: The module cannot simultaneously transmit and receive data, which may limit real-time communication capabilities.

The **ESP8266 Wi-Fi module** is a popular low-cost wireless solution that allows microcontrollers to connect to Wi-Fi networks. It supports full-duplex communication and has a much higher data rate than RF modules like the HC-12.
How the ESP8266 Works:

- The ESP8266 communicates with the Arduino Mega using the UART serial interface, just like the HC-12. It can also operate as a standalone microcontroller with its own firmware and integrated TCP/IP stack.
- Once connected to a Wi-Fi network, the ESP8266 can send data to a remote server or a local device (e.g., a laptop) via the HTTP protocol or using socket connections.

Advantages:

- High Data Rate: The ESP8266 can transmit data at much higher speeds compared to RF modules, with data rates reaching several Mbps, making it ideal for applications requiring high bandwidth.
- Full-Duplex Communication: Unlike the HC-12, the ESP8266 can send and receive data simultaneously, improving communication efficiency.

Disadvantages:

- Shorter-Range: Wi-Fi typically has a range of 50–100 meters, significantly less than the range provided by the HC-12.
- Higher Power Consumption: Since Wi-Fi communication requires more power, the ESP8266 consumes more energy than the HC-12.

To determine the best communication module for our hydrofoil system, several factors were considered:

1. **Distance of Communication**:
   For long-distance applications, the HC-12 was preferable due to its superior range of up to 1.8 km. However, if the boat is operating closer to the shore or within Wi-Fi range, the ESP8266 provides better data rates and functionality.

2. **Latency of Communication**:
   Latency was a critical factor in ensuring the boat's real-time performance could be monitored. The ESP8266 offered lower latency due to its faster data transmission capabilities, but it was limited by range. The HC-12 had slightly higher latency due to its lower data rate, but its long-range made it useful for certain scenarios.

3. **Effect of Communication Module on the Main Microcontroller**:
   While both the HC-12 and ESP8266 require a UART interface for communication, the ESP8266 has less of an impact on the microcontroller's processing power. This is because the ESP8266 is capable of handling the transmission of data packets on its own processor. In contrast, the HC-12 relies on the

microcontroller to prepare and manage the data packets for transmission, requiring more processing resources from the microcontroller. Therefore, implementing the HC-12 places a higher processing burden on the microcontroller compared to the ESP8266.

4. **Ease of Use and Functionality**:
   The ESP8266 offers more flexibility and features, such as the ability to set up a web server and transmit data via HTTP or WebSocket protocols. This makes it easier to visualize the boat's real-time data on a web-based interface. The HC-12, while limited in functionality, was easier to set up and use, making it ideal for simple long-range communication tasks.

5 Final Design and Outcomes

5.1 Building and Construction of the Hydrofoil

5.1.1 Hull Design

The design of the catamaran hull was a collaborative effort with Tiziano Wehrli, who was responsible for performing the buoyancy calculations and optimising the hull structure. The primary goal was to enhance stability without compromising the available space for electronic components. The catamaran design consists of two pontoons and a main hull, which houses all the critical electronics and offers sufficient space for experimentation. The pontoons were left empty to provide buoyancy, while lightweight and durable materials, such as plywood reinforced with resin and fibreglass, were chosen to balance structural integrity and reduce weight. A labelled diagram of the hull design is shown in Figure 5.1.

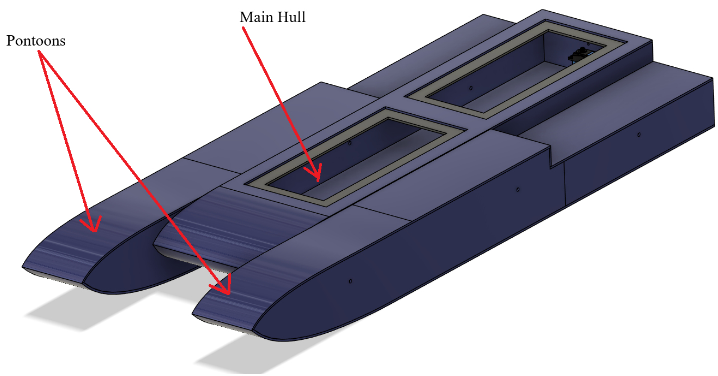

Figure 5.1: Catamaran Hull Design

5.1.2 3D Modelling and Design Approach

The wing profile selected for the hydrofoil was the NACA 2412, a well-documented and extensively researched airfoil. This profile was chosen for its simplicity and proven performance across a range of conditions, ensuring a strong foundation for our design. The NACA 2412 profile was designed at a **0-degree** angle of attack to establish a baseline for future design iterations. At this angle, the coefficient of lift for the wing was approximately $C_L = 0.3145$, providing adequate lift for initial theoretical trials.

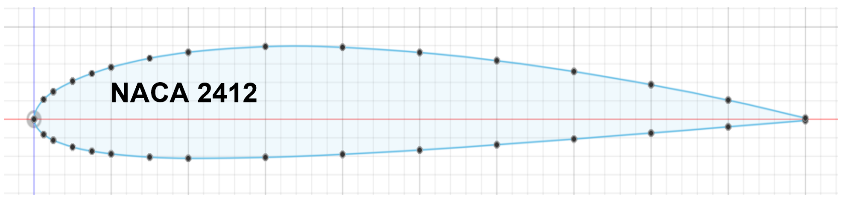

Figure 5.2: NACA 2412 Airfoil Profile

For the aspect ratio, a **moderate value of** $AR = 5$ was selected. This was a balanced choice to avoid the structural challenges posed by a high aspect ratio, which could cause breakage due to the forces experienced underwater, particularly given our use of PLA material. Conversely, a low aspect ratio would have resulted in excessive drag and a bulky structure. The chosen aspect ratio allowed for optimal performance while maintaining structural integrity.

Fabrication accuracy was a critical consideration during the design process. Given the limitations of available equipment, achieving exact positioning of the wings and precise center of gravity measurements was not feasible. As a result, torque equations were not applied to balance the lift between the front and rear wings. Instead, to simplify the fabrication and design process, it was ensured that the front wings (main wings) could lift the entire expected mass of the hydrofoil, which was approximately **10 kg (L = 98 N)**. Depending on the final placement of the back rudder/mast, the rear wing could be adjusted accordingly. Therefore, the sum of the lift in the y-direction exceeded the required lift for the 10 kg mass.

The wings were also designed to accommodate a maximum speed of 20 km/h ($V = 5.56m/s$). This design consideration was crucial since the maximum speed would be achieved during takeoff, where the greatest lift and forces would be experienced. Once in cruise mode, the lift requirements would decrease.

For fluid density, the water temperature was assumed to be 25°C, resulting in a water density of approximately ρ =**997 kg/m^3**. This value was used, along with the equations outlined in Section 4.2.2, to calculate the initial chord length and wingspan for the hydrofoil. The back wings were designed smaller than the front wings because their greater distance from the CoG provides a longer moment arm. As a result, they require less lift than the front wings to produce the same magnitude of moment.

The initial dimensions of the hydrofoil wings are shown in Table 1.

Table 1: Dimensions of Front and Back Wings

Wing Type	**Wingspan (mm)**	**Chord Length (mm)**
Front Wings	312	63
Back Wings	156	63

The masts were designed to be hydrodynamic, minimizing drag while still accommodating control rods. As a result, the Eppler 862 strut wing profile was selected. This symmetrical profile provided a large cross-section necessary for housing the control rods without generating lateral forces that could affect the boat's stability. The simplicity of this profile also contributed to ease of fabrication.

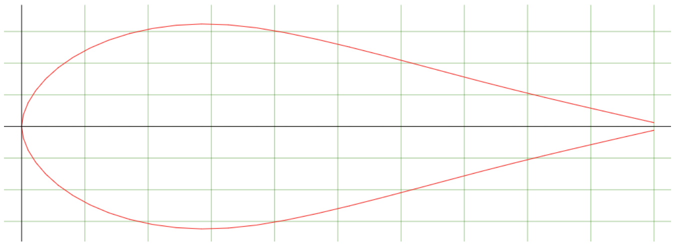

Figure 5.3: Eppler 862 Strut Wing Profile

The 3D modelling of the hydrofoil system was conducted using Autodesk Fusion 360, which allowed for team collaboration by syncing designs to cloud storage. This collaborative environment facilitated efficient design iterations, as changes could be shared and reviewed in real time. During the 3D modelling phase, special attention was given to material selection and modularity to ensure the project could meet its budget constraints while allowing for rapid prototyping.

In the early prototyping stages, PLA and PETG were selected as the primary materials due to their affordability and compatibility with 3D printing. These materials allowed for quick iterations during the design validation process.

A render of the hydrofoil boat with all components mounted is shown in Figure 5.5. The back mast assembly is shown in Figure 5.4, and the front mast assembly is shown in Figure 5.6. The masts were split into two parts, as the lower part of the mast attaches to the wings, while the upper part mounts to the hull, this allowed for iterations of how the mast attached to each component without reprinting the entire mast. The exploded view of the front mast assembly is shown in Figure 5.7. Furthermore, the modularity allowed us to decrease the print time and material usage, as only the necessary parts were printed for each iteration, reducing waste and cost.

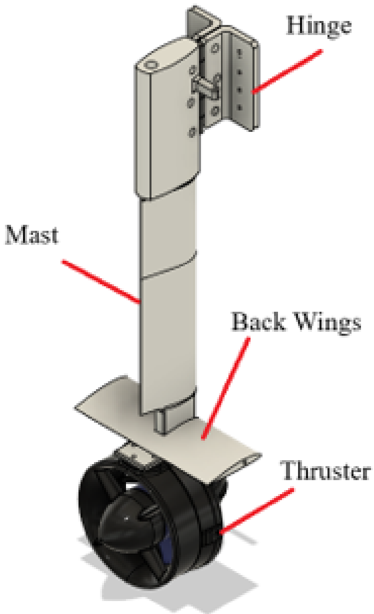

Figure 5.4: Back Mast Assembly.

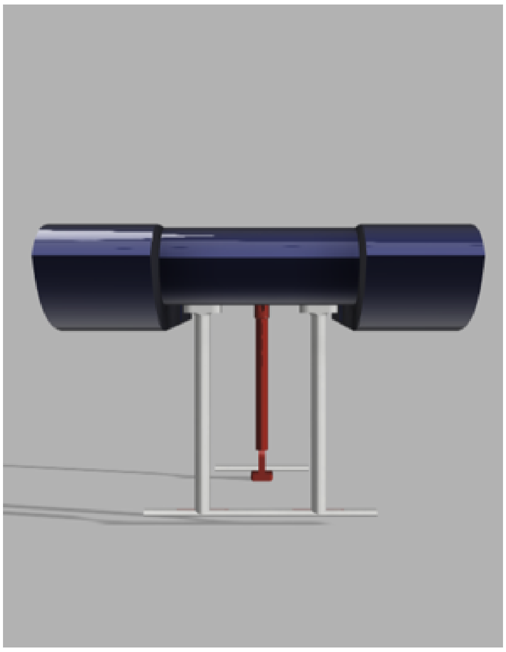

Figure 5.5: 3D Render of the hydrofoil boat with all components mounted.

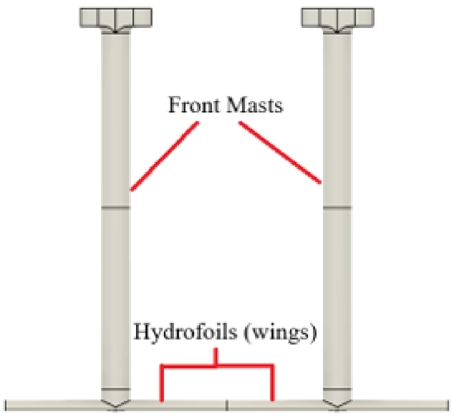

Figure 5.6: Front Mast Assembly.

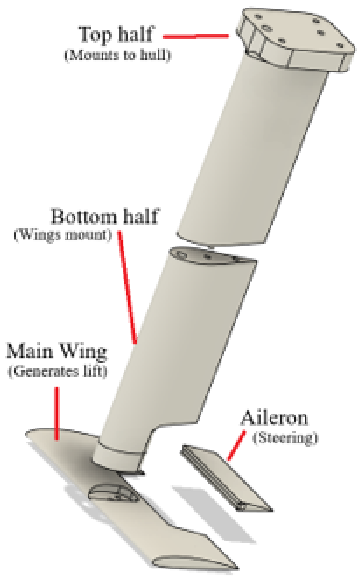

Figure 5.7: Explosion Diagram of Front Mast Assembly.

5.1.3 Build Phase

Manufacturing Methods:

The primary manufacturing technique for this project was 3D printing, offering the flexibility to quickly prototype and refine various components of the hydrofoil system.

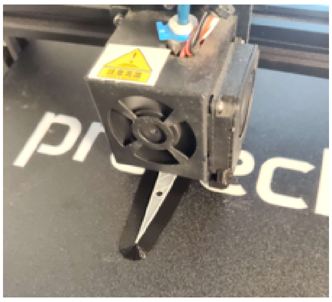

Figure 5.8: 3D-Printer in Progress

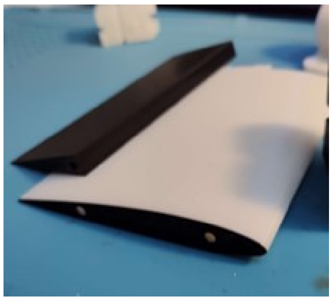

Figure 5.9: 3D-Printed Part.

Figure 5.10: Before and After primer coating.

Figure 5.11: Initial part compared with painted part

3D printing as shown in Figure 5.8, also known as additive manufacturing, works by creating objects layer by layer from a digital model. The printer deposits material in successive layers until the final shape is formed. The slicing software used for this process was Ultimaker Cura. Slicing refers to the process of converting a 3D model into a set of instructions that the 3D printer can follow. The software "slices" the model into thin horizontal layers depicted in Figure 5.12 and 5.13, and for each layer, it generates the corresponding tool paths and printer settings.

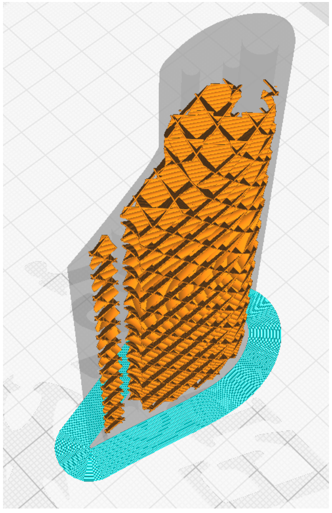

Figure 5.12: Cura Slicer - infill depiction.

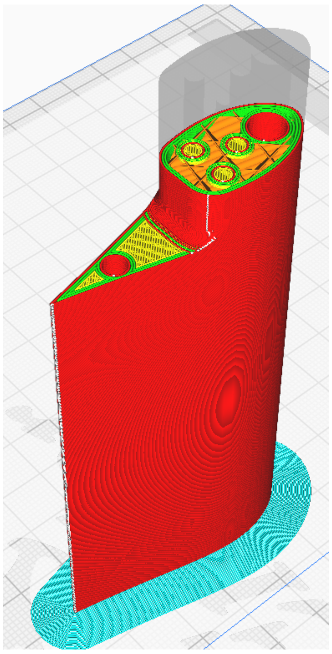

Figure 5.13: Cura Slicer - layer abstraction of model.

Each individual part of the wing assembly took, on average, 6 hours to print, depending on the complexity and size of the part. An example of a 3D printed part is shown in Figure 5.9.

Surface Finishing:

Due to the layer-by-layer nature of 3D printing, post-processing was required to improve both the aerodynamic performance and aesthetic quality of the parts. This was achieved through progressive sanding, starting with coarse grit and progressing to finer grit sandpapers. After smoothing, the components were coated with multiple layers of primer, as shown in 5.10 to reduce surface roughness and enhance durability, followed by painting for further protection and improved appearance. The final painted part is shown in Figure 5.11.

Structural Reinforcement:
Critical load-bearing sections, especially the hydrofoil wings and mast, were reinforced using 316 stainless steel rods. These rods were chosen for their high strength and corrosion resistance, essential for maintaining structural integrity during testing and operation. The metal rods were embedded within the printed components to distribute forces more evenly and prevent deformation. The shiloutte of the reinforcement is shown in Figure 5.14. The rods also provided additional support for joining the two halves of the wings, ensuring a secure and robust connection.

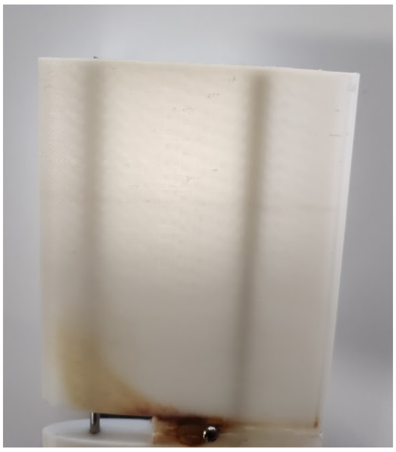

Figure 5.14: Stainless steel rod reinforcement.

Iterative Testing and Assembly
An iterative approach was adopted during the build process, ensuring that each part of the hydrofoil system was tested and assembled individually before final system integration.

Testing allowed for rapid design iterations. Components that failed to meet performance expectations were modified based on test data, with adjustments made to dimensions, angles, or materials as needed. This approach ensured that each part of the system met the required performance standards before being integrated into the larger system.

Figure 5.15: Wing assembly mounted.

Aileron Actuation

The ailerons on the front masts were essential for controlling the hydrofoil's pitch and maintaining stability. To ensure reliable operation, a waterproofed actuation mechanism was designed. As there were two ailerons, and each were controlled separately - two control rods were required. This is what resulted in the choice of having two masts as seen in Figure 5.15, each serving as a mount for the wings and a channel for their corresponding control rods.

The ailerons were controlled using gauge wires connected to servos mounted inside the hull. These servos were waterproofed to protect them from water exposure, and the gauge wires were routed through the hollow masts to the ailerons, ensuring safe and reliable control. The servos, powered by the central Arduino Mega, provided precise adjustments to the ailerons during operation. Guage wires were chosen for their flexibility and resistance to corrosion, ensuring reliable actuation of the ailerons.

5.1.4 Challenges Faced

Speed Limitation:

A major challenge during testing was the system's inability to achieve the target speed of 20 km/h. Initial tests showed that the system could only reach a maximum speed of 3 km/h, far below the expected performance. This speed limitation affected the hydrofoil wing design, as the original parameters were based on higher speeds.

Motor Replacement:

To address the speed limitation, the original T200 thruster was replaced with a more powerful brushless motor coupled with a custom propeller. The new motor provided higher thrust, allowing the system to achieve speeds closer to 6 km/h.

Figure 5.16: Initial thruster used - T200.

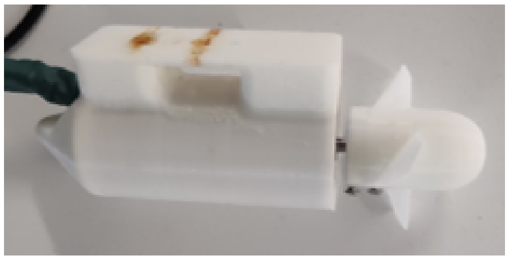

Figure 5.17: Brushless motor used as a replacement with custom propeller.

Wing Angle of Attack Adjustment:

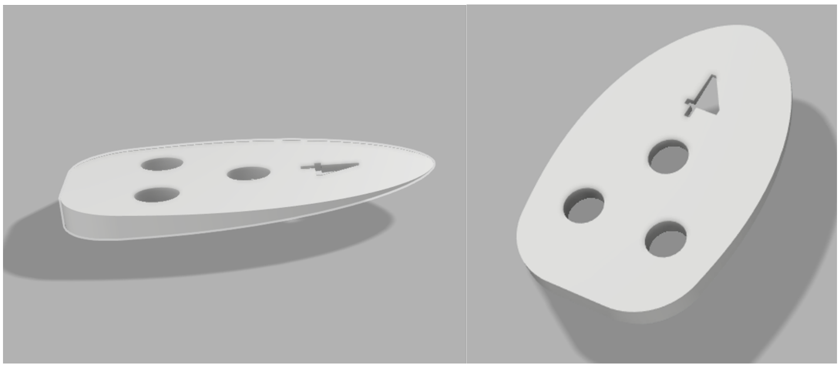

Figure 5.18: Design of offsets to adjust the angle of attack (4 degree offset).

The initial design of the hydrofoil wings used a NACA 2412 airfoil profile at a zero-degree angle of attack. However, at the lower speeds of 6 km/h, the angle of attack had to be increased to generate more lift, otherwise the wing dimensions would have to be increased - but that would have resulted in a larger hydrofoil system. To address this, adjustable offsets were designed, as shown in Figure 5.18, to increase the angle of attack which increased the coefficient of lift.

Thanks to the modularity of the hydrofoil design, it was possible to adjust the angle of attack without reprinting the entire wing. This allowed for rapid testing and experimentation with different angles of attack, ensuring minimal delays during the build phase. Figure 5.19 shows the offsets in place between the mast and wing interface.

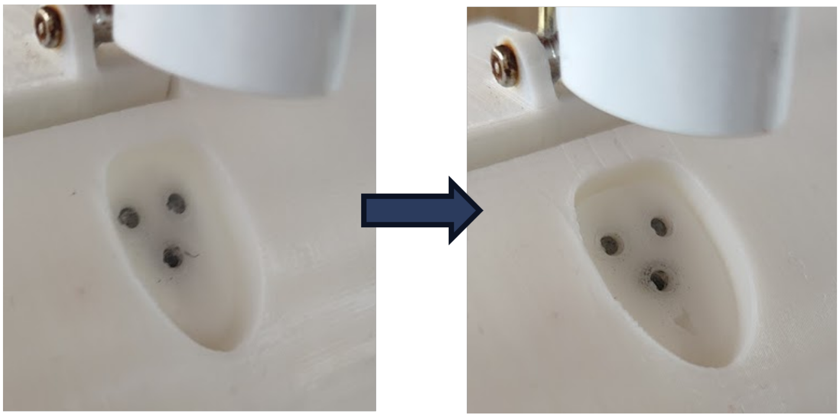

Figure 5.19: AoA offsets in place, between the mast and wing interface.

After plotting the wing data available [21], a 4-degree angle of attack was determined to provide the best lift-to-drag ratio of 27.92 for the NACA 2412 profile, which can be seen from Figure 5.20. This increased the Coefficient of Lift (C_L) and enabled the wings to generate sufficient lift at lower speeds without causing excessive drag.

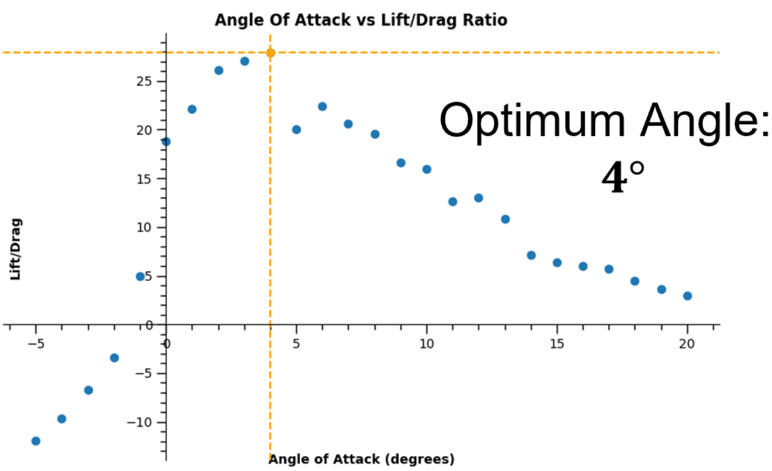

Figure 5.20: Plot to find the optimum lift/drag ratio for a given AoA.

Revised Wing Dimensions:

To compensate for the lower speed, a larger wingspan was required to generate sufficient lift. The lift equation (1) was recalculated, and the reference area A (wingspan multiplied by chord length) was increased to maintain the necessary lift. This adjustment ensured that even at lower speeds, the hydrofoil could generate enough lift to perform adequately. The final wing dimensions are shown in Table 1 and a comparison of the old and new wings is shown in Figure 5.21.

Table 2: Comparison of Initial and Final Wing Dimensions

Wing	**Wingspan (mm)**	**Chord Length (mm)**
Initial Wings	312	63
Final Wings	442	88

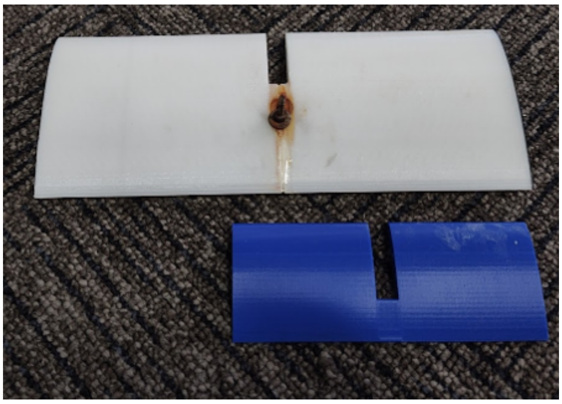

Figure 5.21: New wing (white) compared to old wing (blue).

Back Wing Stability Issue:

Another challenge arose with the back wing, which was generating too much lift, disrupting the overall balance of the hydrofoil system.

The excessive lift from the back wing created excessive counterclockwise torque that counteracted the main wing's lift, preventing the hydrofoil from stabilizing and lifting out of the water as intended.

Adjustable Back Wing Angle of Attack:

To correct this, the mounting system for the back wing was redesigned, allowing for adjustable angles of attack, the 3D-render can be seen in Figure 5.22. The revised method was to use a lead screw and secure the backwing using a bolt, this created a hinge where the backwing could rotate, allowing the AoA to be changed. Through testing and experimentation, the back wing angle was optimized, ensuring a balance between the lift produced by both the front and back wings. This modification depited in Figure 5.23 was critical for achieving stable hydrofoiling.

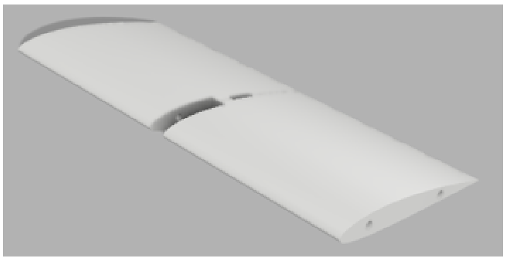

Figure 5.22: Design of adjustable back wing.

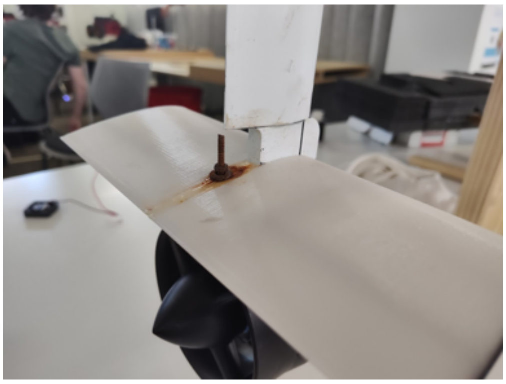

Figure 5.23: Adjustable back wing mounted.

5.1.5 Final Design Outcome

The hydrofoil system underwent several design iterations and modifications to address the challenges faced during the build phase. The final build and assembly is shown in Figure 5.24 and 5.25. The final design specifications are summarized in Table 3

Figure 5.24: Final build of the hydrofoil (front view).

Figure 5.25: Final build of the hydrofoil (side view).

Table 3: Final Hydrofoil System Specifications

Parameter	**Value**
Material	PLA, PETG, 316 Stainless Steel
Maximum Speed	6 km/h
Aspect Ratio	5
Front Wingspan	442 mm
Front Chord Length	88 mm
Front Wing Angle of Attack	4°
Front Wing Coefficient of Lift	1.1854
Front Wing Lift	98 N
Front Wing Distance from CoG	60 mm
Back Wingspan	221 mm
Back Chord Length	88 mm
Back Wing Angle of Attack	0.5°
Back Wing Coefficient of Lift	0.4367
Back Wing Lift	11.76 N
Back Wing Distance from CoG	500 mm

5.2 Implementation of Communications and Sensors

5.2.1 Internal Communications

IMU: I2C Communication Protocol

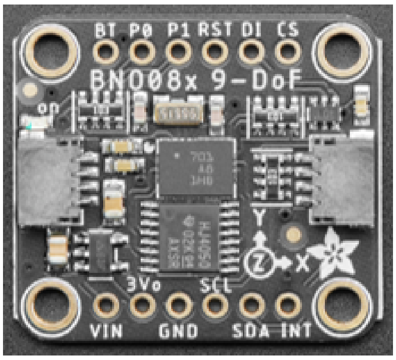

Figure 5.26: BNO085 IMU for Hydrofoil System

For the hydrofoil system, the **Adafruit BNO085 IMU** was utilized, a highly accurate and versatile 9-axis inertial measurement unit (IMU) as shown in Figure 5.26. This sensor provides detailed data on acceleration, rotation rates (gyroscope), and magnetic fields, enabling comprehensive motion tracking. The selection of the BNO085 was driven by its precision and integrated features, which include:

- **Precise Orientation Tracking:** The BNO085 features a built-in fusion algorithm that combines data from its accelerometer and gyroscope to provide highly accurate orientation information. This made it ideal for tracking the pitch and roll of the hydrofoil during operation, a crucial element for stability control.

- **Gyroscope Accuracy:** The gyroscope on the BNO085 excels in delivering stable and precise angular velocity data. This capability was leveraged to accurately measure the pitch of the hydrofoil, ensuring smooth adjustments in real-time to maintain the desired angle of attack.

- **Multiple Communication Protocols:** The BNO085 supports UART, I2C and SPI communication protocols, offering flexibility in interfacing with microcontrollers such as the Arduino Mega and ESP8266.

For this application, I2C was selected for the IMU because of its minimal wiring requirements and the ease of integration with our main control system. Additionally, I2C's ability to run at data rates between 100kbps (standard mode)and 400kbps (fast mode) provided more than sufficient bandwidth for the IMU's output. Since our main program loop was running at a frequency of 50Hz, the lower bound of the I2C data rate was more than adequate for reliable data transmission without any loss of sensor data.

Ultrasonic Sensor and GPS: UART Communication Protocol

Figure 5.27: Ultrasonic sensor for distance measurement.

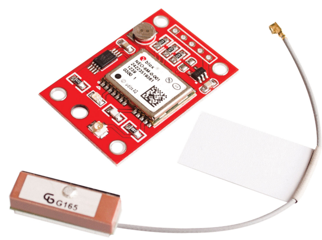

Figure 5.28: GPS module for real-time position tracking [32].

For the ultrasonic sensor (Figure 5.27) and GPS (Figure 5.28), the **UART (Universal Asynchronous Receiver-Transmitter)** communication protocol was used.

UART provides a simple, robust communication channel that is well-suited for peripherals such as GPS modules and ultrasonic sensors, which typically transmit data at slower rates compared to high-frequency sensors like IMUs. Since UART operates independently of a clock signal, it allowed for reliable communication over long distances. This was particularly useful in routing data from these sensors to the microcontroller without timing issues. Furthermore, the GPS module's baud rate (typically set around 9600 bps) was perfectly aligned with the capabilities of the UART interface, ensuring smooth data flow.

GPS Module: Ublox Neo-6M

We used the **Ublox Neo-6M GPS module** for this project, which is known for its high accuracy and fast update rate, making it suitable for real-time navigation applications.

- **Operation**: The Ublox Neo-6M communicates with the main controller via a **serial interface (UART)** and provides the boat's real-time position in the form of **NMEA sentences**. These sentences contain essential data such as latitude, longitude, and speed, allowing the boat's position to be tracked in real-time.
- **Baud Rate**: The GPS module was configured to operate at a standard baud rate of **9600 bps**, ensuring a reliable communication rate that was adequate for the boat's navigation and control needs.

Ultrasonic Sensor: HC-SR04 Module

The **HC-SR04 ultrasonic sensor** was used to measure the distance between the boat and the water surface, which is critical for maintaining the boat's height above water during hydrofoiling.

- **Operation**: The HC-SR04 operates by emitting sound waves from a **trigger pin**, which bounce off the water surface and are received back at the **echo pin**. By measuring the time taken for the echo to return, the distance to the water surface can be calculated.
- **Trigger and Echo**: The sensor sends out a short **ultrasonic pulse** (sound wave) at a frequency of 40 kHz. The time it takes for the pulse to return is measured, and this value is used to calculate the distance between the sensor and the water. The formula for calculating the distance is:

$$\text{Distance} = \frac{\text{Time (microseconds)} \times 343\,\text{m/s}}{2} \tag{6}$$

  where 343 m/s is the speed of sound in air, and the division by 2 accounts for the round trip of the pulse.

- **Communication**: The sensor communicated with the microcontroller using the **UART protocol**, ensuring reliable data transmission even in outdoor and dynamic conditions.

5.2.2 Remote Communication: ESP8266 for Wi-Fi Connectivity

To facilitate remote communication with the hydrofoil system, an ESP8266 Wi-Fi module was integrated. This module was chosen for its reliable Wi-Fi capabilities, ease of use, and extensive community support, making it a cost-effective solution for sending and receiving data over the internet.

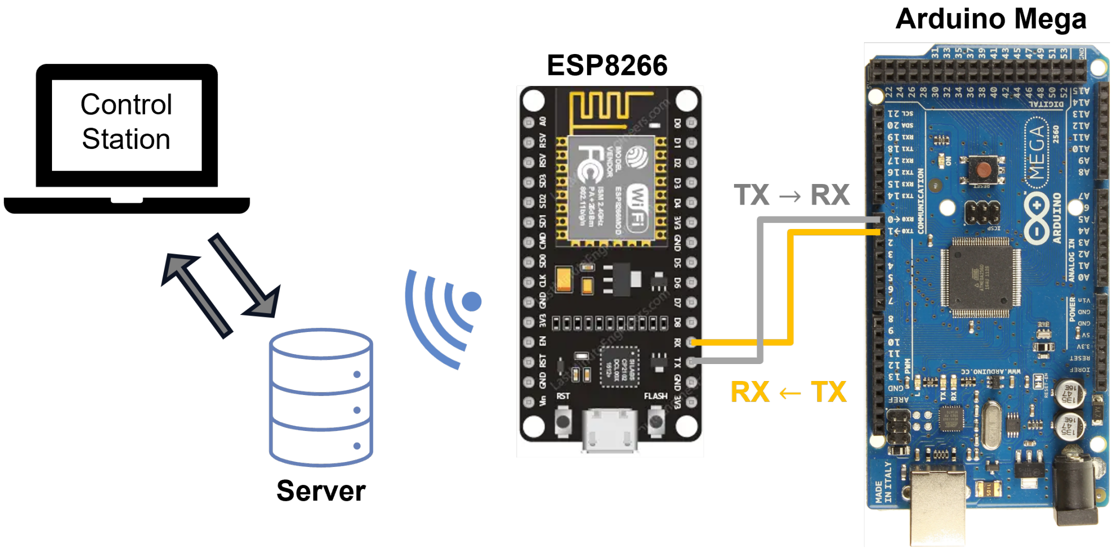

Figure 5.29: Usage of ESP8266 for Wi-Fi connectivity and web server hosting.

- **Cloud Data Transmission:** The ESP8266 was primarily used to send real-time data to the cloud for monitoring and analysis. It enabled us to stream crucial system parameters such as the pitch, speed, and control loop data, allowing remote monitoring of the hydrofoil's performance. This feature proved essential during testing, as it provided real-time feedback on the system's behavior without the need for physical access.

- **Control Loop Tuning:** In addition to data monitoring, the ESP8266 also allowed for remote control loop tuning. By streaming control loop parameters to the cloud, the PID controller values could be adjusted and fine-tuned remotely, optimizing the hydrofoil's stability and responsiveness. This wireless tuning capability significantly enhanced the efficiency of our testing process, as changes could be made and tested quickly and easily.

- **Remote Calibration and Commands:** The ESP8266 was further utilized for sending calibration commands to the onboard systems. During field tests, this feature enabled remote recalibration of sensors such as the IMU, eliminating the need for manual intervention. The module also has the potential to serve as a remote monitoring and control station, where future expansions could include additional functionality such as initiating or halting operations via a remote base station.

Overall, the ESP8266 proved to be an invaluable component of the hydrofoil system, enabling remote diagnostics, data streaming, and control, all of which contributed to a more flexible and efficient testing environment.

5.3 Implementing Control Systems

The control system was implemented after the hydrofoil design was able to lift the boat out of the water. Figures 5.30 and 5.31 show the boat taking off and foiling, respectively.

Figure 5.30: Final hydrofoil design taking off

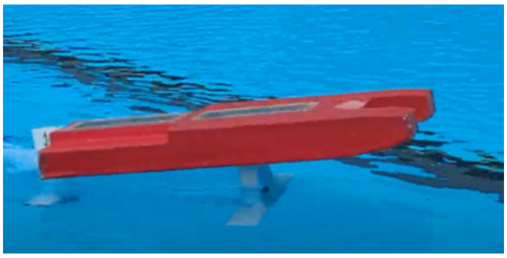

Figure 5.31: Final hydrofoil design foiling

5.3.1 Sensors

A key aspect of the hydrofoil design was the selection of sensors and the development of an effective control system. Various sensors were used to provide real-time data on the boat's motion and position. An **Inertial Measurement Unit (IMU)** was employed to gather data on the boat's **roll**, **pitch**, and **yaw**, which was crucial for maintaining stability during hydrofoiling. The control system relied on an **Arduino Mega** microcontroller to interface with the sensors and actuate the thruster propulsion system.

For height estimation above the water surface, both **capacitive water level sensors** and **ultrasonic sensors** were explored. Using multiple sensors for redundancy was essential for maintaining accuracy and ensuring robust performance under different conditions. These sensors fed data into the control loop to adjust the hydrofoil's height dynamically, maintaining optimal performance and stability.

We tested two primary sensor types to determine the boat's height above the water surface:

- **Capacitive Water Level Sensor**: This sensor works by detecting changes in the capacitance of water, providing continuous feedback on the water level. However, it was highly sensitive to water conditions, such as salinity and debris, making it less reliable in real-world, turbulent environments.
- **Ultrasonic Sensor**: The ultrasonic sensor works by emitting sound waves and measuring the time taken for the reflected waves to return, calculating the distance to the water surface. This sensor performed better in various water conditions, as it was not affected by salinity or debris. However, it still faced challenges in highly turbulent waters, where readings could become inaccurate.

The **ultrasonic sensor** was selected due to its robust performance in outdoor and varied water conditions. It communicated with the Arduino using the **UART protocol**, providing stable and accurate height data during testing. The ultrasonic sensor played a critical role in maintaining the correct height above the water and fed essential data into the control loop for height adjustment.

5.3.2 Developed Control Loop

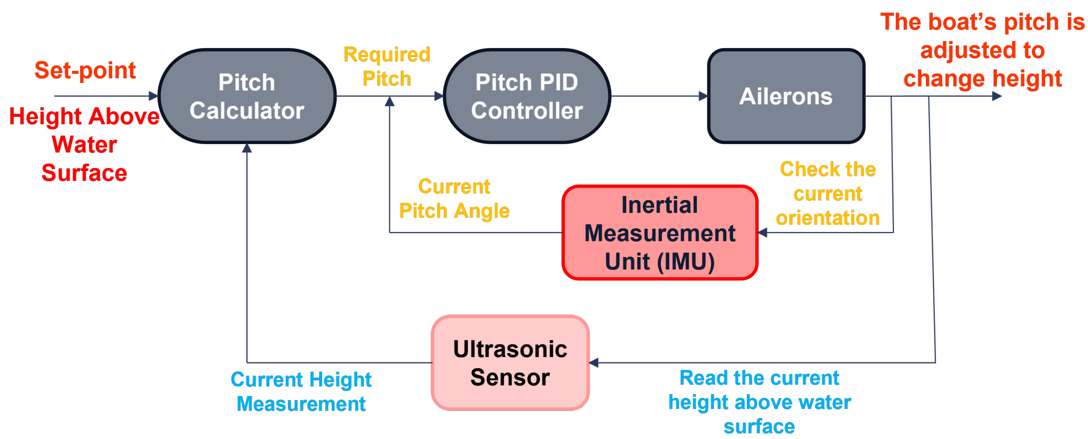

Figure 5.32: Control Feedback Loop Diagram

Once the boat reached hydrofoiling speed, it entered a naturally **unstable condition**, where external forces such as wind and waves could easily disturb it. This necessitated the development of an effective control system to stabilize the boat and maintain smooth operation. The control system relied on both **PID** and **cascade control loops** to manage the boat's **height** and **pitch** simultaneously.

The **IMU sensor** provided gyroscopic data that was used in a **PID control loop**. The PID controller adjusted the ailerons to maintain the correct pitch angle, as follows:

- **Proportional Control (P)**: Continuously compared the boat's actual pitch angle to the desired setpoint, using the error to make real-time adjustments to the ailerons.
- **Integral Control (I)**: Summed up the past pitch errors to eliminate any persistent offset that proportional control might leave.
- **Derivative Control (D)**: Predicted future errors based on the rate of change of pitch, helping to stabilize the system and prevent overshooting.

This PID loop allowed the boat to maintain a stable pitch during operation, compensating for disturbances in real time.

The system employed a **cascade control strategy** to integrate both height and pitch control. The **outer loop** controlled the height, while the **inner loop** handled pitch adjustments:

- **Outer Loop (Height Control)**: Used the ultrasonic sensor to monitor and maintain the boat's height above the water. If the boat strayed from the target height, the outer loop would adjust the pitch to correct it. The sensor was connected over UART and hence provided a slower changing system, this outer loop was running at around 30Hz.
- **Inner Loop (Pitch Control)**: The inner loop, managed by the **PID controller**, continuously adjusted the pitch based on data from the IMU. The height control loop's output served as the setpoint for the pitch control loop, allowing for finer adjustments and smoother hydrofoiling. The PID control

loop was running at around a frequency of 50Hz.

The cascade control system allowed for more precise control of both **height** and **pitch**, improving overall stability and performance during hydrofoiling.

5.3.3 Challenges in Control Loop Tuning

- **Limited Aileron Range**: The boat's ailerons were unable to achieve their full range of motion. While they could adjust to pitch the boat upward, they could not pitch it downward adequately. This issue arose from the **wing size and placement**, which had not been adequately accounted for in the design. While the mast was modular, allowing different wing profiles to be tested, the **wing sizes** varied, affecting the maximum speed and control range. The position of the aileron control rods was too close to the hinge point, reducing the ailerons' range of motion.

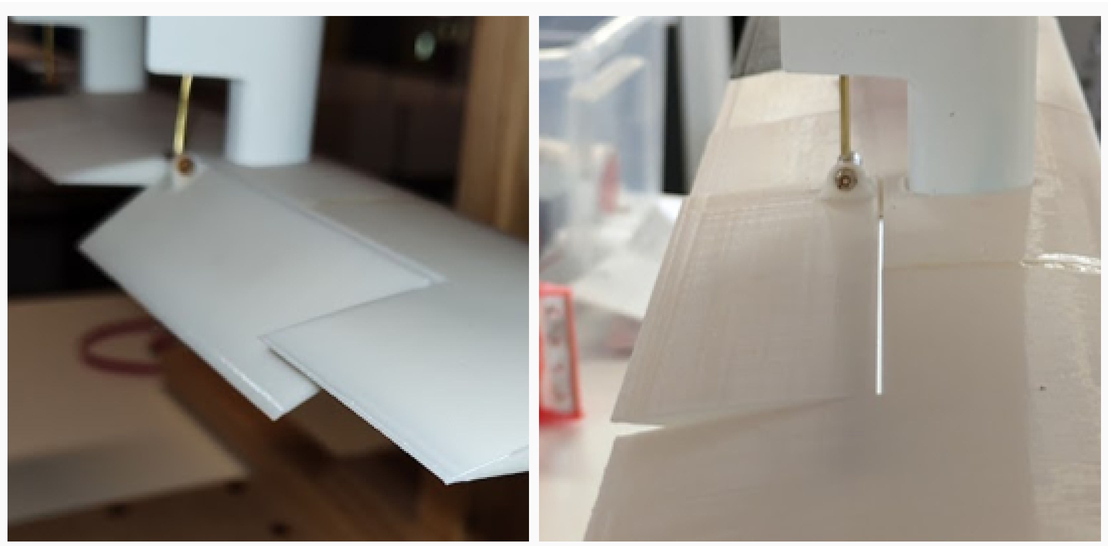

Figure 5.33: Limited Aileron Range

- **Ultrasonic Sensor Water Intrusion**: Although the ultrasonic sensor was mounted away from the water surface, water eventually seeped into the sensor through the holes in the mount designed for sound waves. This made the sensor give **erroneous readings**, compromising the control system's ability to maintain stable height control.

Due to the combined challenges of limited aileron motion and ultrasonic sensor failure, the boat was unable to maintain stable hydrofoiling. These limitations meant that the control loop could not be properly tuned and tuning data for pitch tuning as well as height tuning were erroneous, ultimately the system failed to reach a stable hydrofoiling state. Despite these setbacks, valuable insights were gained into the design and control of hydrofoil systems, highlighting areas for future improvement in sensor selection and control system design.

5.4 Integration of Autonomous Driving and Navigation

Due to the inability of the boat to hydrofoil stably during the test, the autonomous navigation system was tested while the hydrofoil operated as a normal boat, without lifting above the water surface. Testing was conducted in a pool, limiting the scope of our results to yaw control tuning rather than demonstrating the full GPS waypoint navigation system's applicability to hydrofoiling conditions.

5.4.1 GPS Waypoint Navigation System

For long-distance travel and waypoint-based routing, a **GPS waypoint navigation system** was implemented. This method allows the boat to autonomously navigate to predefined coordinates, following a calculated route and making real-time adjustments to maintain the correct heading. Although our tests in the pool did not directly provide insights into how the GPS-based navigation system would function during hydrofoiling, they were useful for tuning yaw control, as discussed in the following sections.

The program was developed in C++ in the Arduino IDE, utilizing the **TinyGPS++** library to parse GPS data. The system was designed to read pre-defined GPS coordinates which were set using Google Maps, allowing for easy modification of waypoints. The boat would then navigate to each waypoint sequentially, adjusting its heading to follow the great circle path between points.

5.4.2 Cascade Control for Navigation

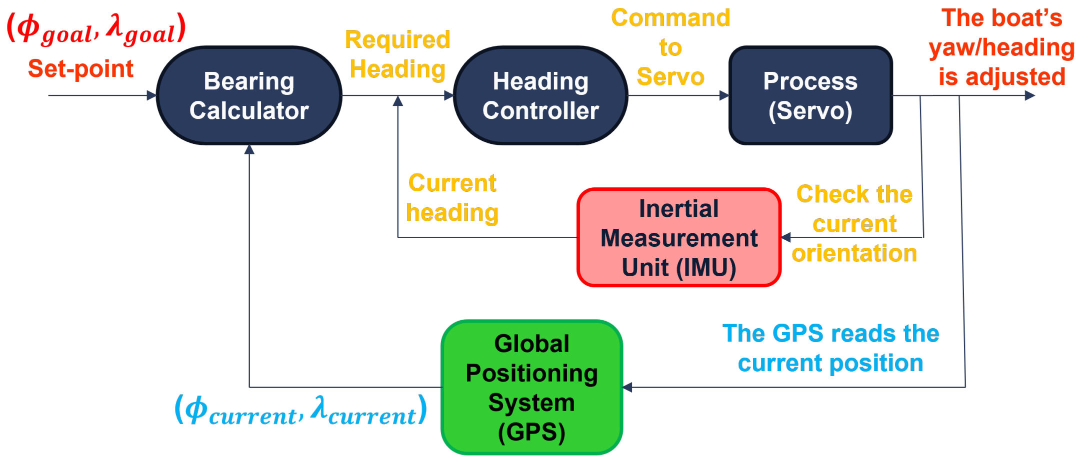

Figure 5.34: Cascade control loop for waypoint navigation

To ensure accurate navigation, a **cascade control loop** was designed, similar to the system used for stabilizing the boat during hydrofoiling. A simle block diagram of the control loop is shown in Figure 5.34. The navigation system was structured with two control loops:

1. **Primary Loop (Bearing Calculation)**:
   - This loop used data from the **GPS** to calculate the current position and determine the required **bearing** to the next waypoint.
   - As the boat moved, this loop continuously updated the bearing using the azimuth equation, ensuring the boat remained on the great circle path.
   - This loop is the slow changing system, and was running at a default frequency of 1Hz, but this was updated by adjusting the GPS module's on-board EEPROM to run at 3.84Hz to improve the accuracy of the bearing calculation.

2. **Secondary Loop (Heading Control)**:

   - The **heading control** was managed by a **PID controller**, utilizing data from the **compass/magnetometer** in the **IMU (BNO085)**. The compass provided real-time heading information respective to true North, which allowed the PID controller to adjust the boat's steering to match the correct heading.
   - The **PID loop** used for the yaw controller designed by Tiziano ensured the boat's actual heading aligned with the calculated bearing from the primary loop, enabling smoother travel.
   - This yaw controller was running at 50Hz as well, as secondary loops in a cascade controller are typically the faster changing system.

By employing this **cascade loop**, the system managed to follow the desired path accurately. The primary loop handled large-scale navigation (bearing calculation), while the secondary loop focused on fine-tuned heading adjustments.

5.4.3 Testing Results and Yaw Control Tuning

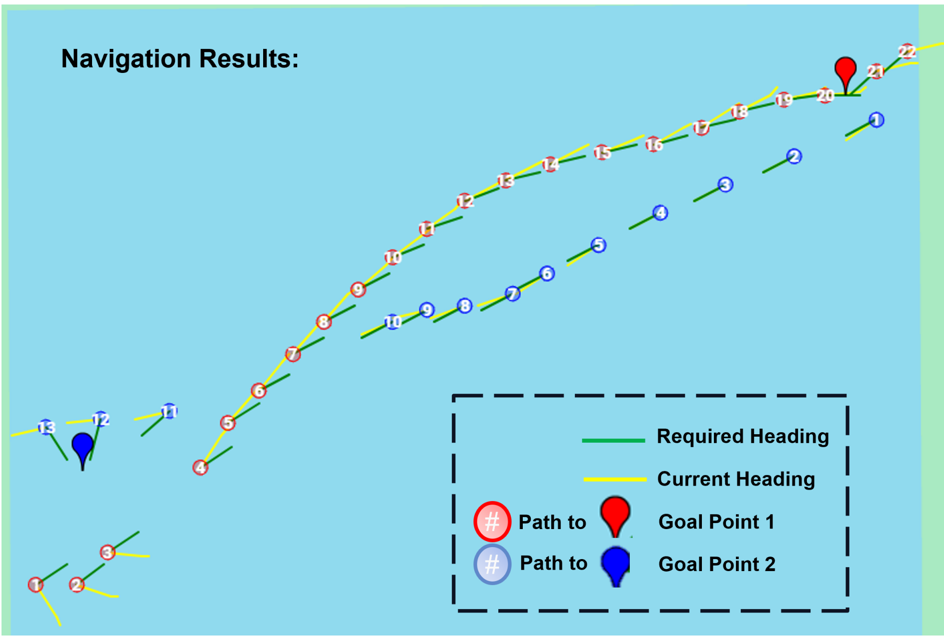

Figure 5.35: Navigation Testing Results

The results of the navigation tests, as seen in 5.35, show the boat's path during two trials: the initial test and a subsequent test after tuning the yaw control. In both cases, the boat overshot the goal point due to the GPS's inherent inaccuracy, which had an error range of **2.5–5 meters**.

- **Initial Test (Red Path)**: The red path in the results represents the initial test. It can be seen that the boat's current heading was consistently offset from the required heading, and while it reached the end goal, the controller was unable to adjust the heading sufficiently to hit the setpoint.
- **Second Test (Blue Path)**: After tuning the yaw control via the **PID controller**, done in collaboration with Tiziano, the second test was conducted. In this case, the boat was able to maintain a heading closer to the required heading, as evidenced by the figure.

The travelled path was generated by plotting the raw GPS data and filtering it using the **Python GLMap library**. This allowed for API calls to **Google Developer Tools/Google Maps**, enabling us to overlay the boat's path on a map. while the API calls to Google Maps required a valid API key and were paid, it provided us with a free student account to use the service and allowed for a better visualization of the boat's path. The other option available was to use the **folium** Python library, which is free to use and uses the open source maps of **OpenMaps**, it did not provide a greater zoom than 18x compared to the 23x zoom provided by GLMap. The factor of zoom was important, as the testing area was relatively small and a clear plot needed to be seen.

6 Analysis and Recommendations

6.1 Analysis of Hydrofoil Build Outcomes

During the construction of the hydrofoil, the primary goal was to develop a system robust enough to allow for the testing and validation of control and navigation algorithms. Rather than optimizing the hydrofoil for performance, emphasis was placed on durability and ensuring a functional test platform. This decision posed several challenges related to the hydrofoil's operational efficiency and its ability to achieve stable hydrofoiling conditions.

The design of the hydrofoil had a significant impact on the overall system performance. As the control and navigation systems were being developed, the hydrofoil's design influenced the stability and efficiency of the vessel. The shape, size, and placement of the hydrofoil wings, as well as the robustness of the overall structure, directly affected the hydrofoil's speed, maneuverability, and ability to maintain height above the water surface. These factors played a crucial role in the control algorithms' effectiveness, as any instability in the hydrofoil's operation would result in difficulties maintaining a smooth and stable path.

Several issues arose during the build process. Being the team's first hydrofoil project, there was limited time to optimize the design. Initially, the hydrofoil was unable to reach the target speed of 20 km/h, achieving only 3 km/h. This issue led to the replacement of the original T200 thruster with a brushless motor coupled with a custom propeller, which increased the speed to 6 km/h. Another issue was identified later in the design process when the wing sizes were increased. This modification impacted the functionality of the ailerons, which could not achieve their full range of motion due to poor placement of control rods. The proximity of the control rods to the hinge point limited the ailerons' effectiveness. Due to time constraints, these issues were not fully addressed, preventing the hydrofoil from achieving stable flight.

6.2 Control System Outcomes

The control systems were successfully implemented from a software standpoint, but the physical design and build limitations of the hydrofoil greatly affected their performance. The hydrofoil's weight distribution and control mechanisms were not optimized, making it difficult to fine-tune the control loop. Although the control systems were designed to maintain stability and height during operation, the hydrofoil struggled to respond effectively to the controller's commands, leading to suboptimal performance.

Moreover, the decision to use cost-effective sensors compromised the system's reliability. These sensors produced inaccurate data, which hindered the control system's ability to make real-time adjustments. The resulting inaccuracies led to poor height control and instability, preventing the hydrofoil from consistently maintaining flight above the water surface.

While the control system software was functional, the hydrofoil's physical constraints limited its ability to achieve the intended stability and height control. The system could adjust the ailerons and rudder in real time to maintain heading and altitude, but the hydrofoil's inability to respond to these adjustments reduced its effectiveness. Testing in both manual and autonomous modes demonstrated the control system's ability to adjust based on user input or predefined GPS coordinates. However, the hydrofoil's instability prevented full testing under hydrofoiling conditions.

6.3 Navigation and Automation Outcomes

Despite the challenges with hydrofoiling, the implementation of the navigation and automation systems was largely successful. These systems allowed the hydrofoil to autonomously navigate to predefined GPS coordinates and adjust its heading in real-time to maintain the correct path. The navigation system was able to calculate the current position, determine the bearing to the next waypoint, and communicate this data to the control system, which adjusted the boat's heading accordingly.

While the navigation system functioned as planned, the hydrofoil's inability to achieve stable flight meant that testing of the full GPS waypoint navigation system under hydrofoiling conditions was not possible. Instead, the system was tested with the hydrofoil operating as a standard boat, allowing for tuning of yaw control but limiting the ability to demonstrate its full capabilities under hydrofoil conditions.

6.4 Applicability of the Project

This project successfully demonstrated the implementation of control and navigation systems in a hydrofoil. However, the physical limitations of the hydrofoil's design and build process prevented these systems from achieving the desired stability and height control. This outcome highlights the complexity of designing hydrofoils and highlights the need for careful consideration of both the design and construction phases in future projects.

Despite the challenges faced, the hydrofoil system developed serves as a proof of concept. The modular design allows for future upgrades and testing, providing a platform for the ongoing development of control and navigation systems. The insights gained from this project will be valuable for improving future hydrofoil designs and control algorithms.

6.5 Recommendations for Future Work

Several key recommendations can be made to improve the performance and applicability of the hydrofoil system in future projects:

- **Improve Mast design:** At the moment the mast accounts for a single wing size, and varying wing profiles, to improve this the mast design should be optimized to accommodate varying wing sizes and configurations. This could involve modifying the control rod shaft with a variable hole system, allowing for greater adaptability. Additionally, replacing the gauze wire used to connect the ailerons to the servos with a more robust and precise gear mechanism would enhance control accuracy. Implementing these changes would significantly improve the overall efficiency of the system, thereby enhancing the performance of both the control and navigation algorithms.
- **Optimize Hydrofoil Design:** The hydrofoil design should prioritize performance optimization, particularly through more detailed simulations such as Computational Fluid Dynamics (CFD) analysis. This will help identify potential issues and improve the hydrofoil's stability and efficiency. Additionally, the hydrofoil's weight distribution should be carefully considered to ensure optimal balance and control. With these changes the hydrofoil will be better equipped to achieve stable hydrofoiling conditions and respond effectively to control inputs.
- **Use Higher Quality Sensors:** Implementing higher quality and waterproof sensors will improve the accuracy and reliability of the system's data. More accurate sensor data will allow the control systems to make better real-time adjustments, leading to improved stability and height control.
- **Upgrade the Microcontroller:** A more powerful microcontroller would enable the use of more sophisticated control algorithms and add functionality to the hydrofoil system. This could include better handling of real-time data and more complex navigation tasks.

- **Test in Real-World Conditions:** Further testing should be conducted in real-world environments, including autonomous navigation trials under hydrofoiling conditions. This will provide deeper insights into the system's performance and allow for more effective optimization.
- **Improve Control Systems:** Future work should focus on optimizing the current control algorithms and experimenting with alternative control methods, such as adaptive or nonlinear controllers, to improve system stability and response times.
- **Add Obstacle Avoidance Systems:** To enhance the system's functionality, obstacle avoidance should be integrated. This will allow the hydrofoil to navigate around obstacles autonomously and handle more complex navigation tasks safely.
- **Additional Sensors:** Including sensors like wind and water current sensors will provide valuable environmental data, allowing for more accurate and adaptive control over the hydrofoil's movements.

7 Conclusions

The development of a conceptual hydrofoil system aimed at testing control and autonomous navigation algorithms has provided valuable insights into the complex dynamics of hydrofoil design, control systems, and navigation technologies. The project successfully demonstrated the implementation of a modular platform for future improvements, offering a foundational proof of concept for the integration of control algorithms, GPS-based navigation, and hydrofoil mechanics. However, several challenges were encountered that highlight the need for further refinements in both design and system architecture.

The construction of the hydrofoil prioritized durability and robustness over performance optimization, which led to significant trade-offs. While this decision allowed for the validation of the control and navigation systems under stable, non-hydrofoiling conditions, it also exposed limitations in speed, maneuverability, and overall system efficiency. Notably, the hydrofoil's inability to reach its design target of 20 km/h necessitated mechanical adjustments, such as replacing the initial thruster with a custom brushless motor. The design issues that restricted the range of motion of critical control surfaces, such as the ailerons, further limited the hydrofoil's ability to achieve stable flight.

The control systems, although effectively designed from a software perspective, were constrained by physical limitations in the hydrofoil's build and the use of budget-friendly, lower-quality sensors. These challenges resulted in unreliable sensor data, which impaired the system's ability to maintain precise height and stability, preventing successful hydrofoiling. Despite these setbacks, the navigation system functioned as intended in non-hydrofoiling tests, demonstrating accurate waypoint navigation and control adjustments.

The results of this project highlights the complexity of hydrofoil design and the necessity for precise engineering in both the physical build and system integration stages. While the hydrofoil did not achieve the desired stable flight, the platform remains a solid foundation for future work, offering a flexible design that can accommodate upgrades and enhancements in performance and functionality.

Several recommendations were made to guide future work, including optimizing the hydrofoil design for performance, using higher-quality and waterproof sensors, upgrading the microcontroller, and testing the system under real-world hydrofoiling conditions. The addition of obstacle avoidance and environmental sensors would further enhance the system's applicability, making it suitable for more advanced maritime operations.

In conclusion, this project marks a significant step forward in understanding and applying hydrofoil control and navigation systems. Though challenges were encountered, the insights gained will be useful in refining future iterations of the hydrofoil, with the ultimate goal of achieving stable, autonomous hydrofoiling performance. With continued optimization and testing, this platform has the potential to contribute to research in the broader field of automated hydrofoil systems.

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