SailBot 2024-2025

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Abstract

This Major Qualifying Project presents the design, development, and testing of an autonomous robotic sailboat for the 2024–2025 International Robotic Sailing Regatta. Building on the foundation laid by previous WPI SailBot teams, the project focused on enhancing performance, reliability, and usability through mechanical, electrical, and software improvements. Key contributions include a redesigned wingsail with improved aerodynamic control and modularity, the addition of a passive rotational damping system, and modified rudders for improved low-speed maneuverability. Electrical upgrades addressed feedback sensing, power management, and the integration of a reliable magnetic power switch. On the software side, enhancements to computer vision, telemetry robustness, and control interfaces improved autonomy and operability. Comprehensive testing validated these systems, and the project demonstrates continued advancement in robotic sailing platforms.

Acknowledgments

We gratefully acknowledge the support and guidance of our advisors, Professor Stafford and Professor Michalson, whose expertise was instrumental throughout the course of this project. We also extend our sincere thanks to Professor Constantinos for his helpful input. We are especially appreciative of Scott Reid for his generous donation of a carbon fiber mast for the new wingsail. Additionally, we thank the Robotics Resource Center for providing access to 3D printers and machining equipment, which were essential to our fabrication process. We recognize Max Brady, Max Valentino, Ben Laster, and our fellow peers for their valuable contributions and collaboration. Finally, we thank previous SailBot teams for their foundational work, detailed documentation, and ongoing willingness to provide insight.

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Executive Summary

This Major Qualifying Project (MQP) focused on advancing WPI's autonomous sailboat platform for the 2024-2025 International Robotic Sailing Regatta (IRSR). The primary objectives were to improve the boat's handling, control, and operational reliability by redesigning key mechanical components, upgrading electrical systems, and refining software.

Mechanically, the team redesigned the rigid wingsail to address limitations in downwind sailing. The new design repositioned the mast to align with the aerodynamic center of the sail, improving rotational balance and enhancing control authority. This modification was validated in controlled lab testing, where the new sail achieved an approximately 10–15° improvement in trim tab response under fan-driven airflow. A viscous damping system was also implemented on the mast to suppress unwanted oscillations. A 1 Hz rocking test confirmed the damper's effectiveness. Additionally, new rudders were fabricated to increase authority when turning the vessel, simulation data indicated a 30–40% improvement in lift supporting enhanced low-speed maneuverability.

Electrical updates focused on system protection and feedback integration. A new Battery Management System (BMS) was designed using the BQ77904 IC, incorporating safeguards against undervoltage (below 3.0V/cell) and overcurrent (above 5A). The system was validated through simulation and endurance testing. A magnetic power switch was successfully implemented, enabling external toggling of power without opening hatches. Feedback sensors were added to the rudder and trim tab servos, providing real-time actuator position data to the control system. These changes improved safety, maintainability, and fault detection.

On the software side, the team addressed vision-based navigation failures from the previous year. The computer vision pipeline was optimized by down sampling image resolution and implementing buoy-passing logic. Object detection accuracy improved, enabling the boat to correctly identify and react to buoys during lab trials. Resource leaks in the telemetry application were addressed, improving system uptime and stability. Delayed wind readings from the Airmar sensor were mitigated using weighted averaging and software filtering, improving tacking accuracy. Additionally, the team implemented robust logging using ROS2's bag system to support post-mission analysis and debugging.

All systems were tested in both simulated and physical environments. Overall, the 2024–2025 SailBot project achieved significant performance improvements across all subsystems. The boat exhibited greater control, increased robustness, and more intuitive operation. The combination of mechanical redesign, electrical protections, and intelligent software updates yielded measurable gains: improvement in rudder lift, reduction in wingsail oscillation, and reduction in CPU load during object detection. These outcomes validate the team's approach and provide a strong foundation for continued success in the International Robotic Sailing Regatta.

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1 | Introduction

The International Robotic Sailing Regatta (IRSR), also known as SailBot, is an annual autonomous sailing competition held across North America. University, college, and high school teams design and build robotic sailboats that can navigate a series of challenges with limited or no human intervention. The competition was first held in 2006 at Queen's University in Kingston, Ontario, inspired by a senior project at the University of British Columbia. Since 2008, IRSR has hosted teams from across the U.S. and Canada, with some traveling from as far as Europe and Brazil.

The goal of the competition is to advance autonomous sailing technology by challenging students to develop systems capable of independent navigation, obstacle avoidance, and long-term operation in unpredictable marine environments. This multidisciplinary challenge requires expertise in mechanical, electrical, and software engineering, as well as engineering management, making it an excellent learning experience for students pursuing careers in robotics, autonomy, and maritime applications.

SailBot teams primarily compete with boats in the SailBot Class, which are up to 2 meters in length, although smaller boats are also common due to their simpler logistics. An Open Class allows larger boats, up to 4 meters, and is oriented toward non-academic teams. Some competitors use the event to test boats for other challenges, such as the MicroTransAt Challenge (which has a 2.4-meter limit) or the World Robotics Sailing Championship (up to 4 meters). Many teams start with platforms like the MaxiMOOP (1.2m) due to its compact size, low weight (20 kg), and higher payload capacity compared to standard RC boats. Figure 1 shows the boat in action on Lake Attitash.

Figure 1: The boat at the 2024 IRSR

The WPI SailBot team has participated in this competition since 2016, competing in the 10th SailBot Regatta at Kingston, Ontario. Last year, the 2023-2024 WPI SailBot team won the competition by remaking the entire hull and control system in the boat. The focus of events in this competition are autonomy, control, and reliability, and these principles guide the design of the boat. The events that we will design the boat to complete involve:

- Autonomously navigating a path marked by buoys
- Station keeping: autonomously maintaining a fixed location
- A long-distance endurance event
- A fleet race
- Locating and colliding with a buoy within a search radius
- Recognizing and avoiding a moving obstacle

This year, our goal is to expand upon the work done by previous WPI teams by remaking the wingsail of the boat, updating the electrical systems, and using the computer vision in navigation. Through these meaningful contributions to the WPI Sailbot, we hope to propel it to victory once more.

2 | Background

2.1 | Mechanical

The mechanical aspects of the boat include the carbon fiber hull, dual rudders, keel, hatches, and a rigid wingsail with an attached trimtab. These systems work together to control the movement of the boat.

2.1.1 | Wingsail

The boat currently uses a freely rotating rigid wingsail that is controlled by a trim tab extending out from the back of the wingsail. The sail itself is two pieces, the top of the sail slots into the main wingsail and is secured magnetically, and the trim tab attaches to the back of the wingsail main body. The mast is made of carbon fiber and has foam ribs attached to it that form the base for the MonoKote wrap secured by vinyl tape. There is also a counterweight that extends from the front of the mast that stabilizes the rotation of the sail, as well as a wind vane that extends from the front of the sail.

The wingsail is an independent subsystem, being controlled by the boat via WiFi. The main wingsail body houses the control box that contains the trim tab electrical components, which is then wired to the servo on the trim tab. There are three fundamental issues that our team has identified with the help of the previous team and our advisors. These are:

- Transportation Resilience: The soft foam of the ribs is prone to breakage or indentation (see Figures 2 and 3), and the thin appendages, which consist of the wind vane and trim tab booms, are fragile as well. However, damage only occurs during transportation and handling of the wingsail
- Interior Access: The only access to the inside of the sail where the electronics are held is a rectangular hole in the bottom rib, and other sections are inaccessible without destroying the MonoKote film
- Point of Sail Range: A running point of sail is the most unstable point of sail because of the way the aerodynamic forces interact and the location of the mast relative to those forces

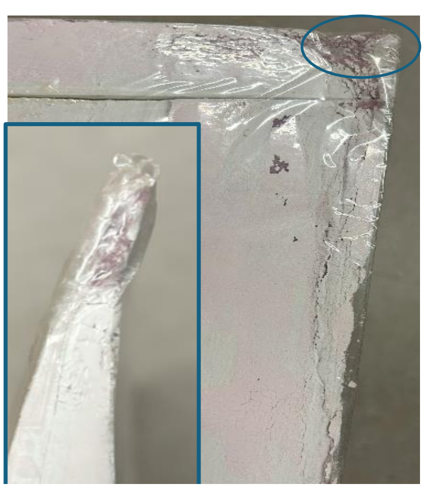

Figure 3: Bottom trailing edge of the top wingsail

Figure 2: Existing Trim Tab

2.1.2 | Rudders

The boat employs a dual rudder system to maintain maneuverability while heeling unlike a traditional single rudder, which tends to lose effectiveness as the vessel heels. The dual rudders, set at an angle of 20°, ensure a maximum moment at a 20° heel enhancing steering control under various conditions. This system is controlled by a single servo connected to both rudders, providing synchronized and efficient turning capability that supports smooth navigation and handling, even when the boat is significantly heeled.

2.1.3 | Keel

Extending approximately 3.5 feet from the bottom of the hull, the keel features a lead weight at its base, which contributes to the vessel's stability by lowering the center of gravity. This lead weight is attached to the boat with a hydrofoil, which further enhances hydrodynamic performance. The keel serves two primary purposes. First, it provides stabilization as the boat heels, enhancing balance and control. Second, it generates lift to counteract the leeward force produced by the sails.

2.1.4 | Linear Ballast

This system consists of a lead weight that can move beyond the edge of the hull on the starboard or port side. Like the keel, part of the purpose of the ballast is to stabilize the heel angle but additionally can induce heeling and optimize the angle. This system is currently defunct after being abandoned at competition last year, the remains of which are shown in Figure 4, and while our team did not reimplement this system, we did use this space for a new addition to the boat.

Figure 4: Defunct Ballast

2.1.5 | Hatches

The vessel is equipped with two access hatches for reaching the interior hull. The primary hatch, a rectangular opening measuring 11.25 by 15 inches and positioned near the stern, provides extensive access to most of the internal electrical and mechanical systems, ensuring ease of maintenance. In addition to this, there is an 8-inch circular hatch located near the bow, which offers supplementary access to other areas of the interior, allowing more convenient handling of additional systems or components that may require attention.

2.1.6 | Mast

The mast is secured in its mounting post by gravity and a 3D printed collar that holds it closer to the center. The mast can freely rotate 360 degrees, but it also has little resistance to small, uncontrolled rocking from the boat due to the wave oscillation on the water.

2.2 | Electrical

The main electrical design includes two custom Printed Circuit Boards (PCB) shown as the main hull in Figure 6 and the sail shown in Figure 5. Descriptions of electronics and sensors used to control the boat are listed below.

2.2.1 | Circuit Boards

The boat currently has two custom PCBs, one in the hull and another in the sail. The main circuit board in the boat, shown in Figure 6, is powered by a 4-cell LiPo battery which powers the Jetson Orin Nano, ESP32, 4G LTE modem, rudder servo motor, Airmar Weatherstation, and ballast motor controller.

The sail circuit board, shown in Figure 5, is powered by a 3.7V LiPo battery which powers the sail ESP32, MA3 digital encoder, and trimtab servo. The battery is connected to a booster to power the ESP32 and encoder via 5V. The board also has a shifter to shift 5V from the encoder to the 3.3V operating voltage for the ESP32.

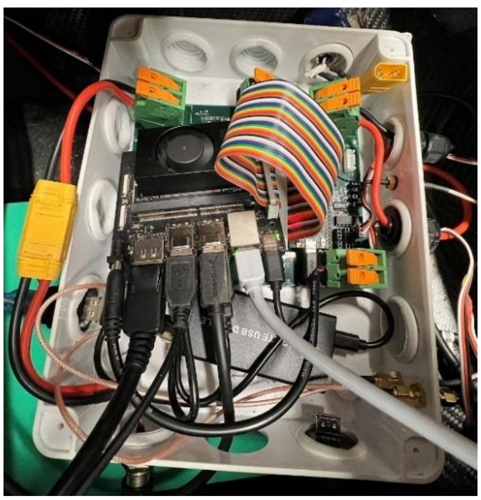

Figure 6: Hull electronics

Figure 5: Sail electronics

2.2.2 | Jetson Orin Nano

This is the primary controller of SailBot which ran Ubuntu 20.04.6 LTS (Focal Fossa). It runs the ROS nodes to control the robot. It also communicates with the ESP32 in the hull using serial communication.

2.2.3 | ESP32 Co-Processor & Sail Controller

The ESP32 in the hull is used as a co-processor as well as communication to the wingsail ESP32 using web sockets. The co-processor is used to send PWM signals to directly control the rudder servo and ballast motor controller. The wingsail ESP32 is used to control the trim-tab servo, read the windvane encoder, and communicates with the hull ESP32 using a Wi-Fi signal.

2.2.4 | 4G LTE Modem

The boat used a 4G LTE modem to connect and communicate to the boat via phone or computer. Using a cellular connection, the boat can receive and transmit data reliably as long as there is cell service in the area. Zerotier is a peer-to-peer networking service used to set a static IP address to the Jetson Orin Nano which allows client devices to connect with the boat.

2.2.5 | Ballast Motor Control

The ballast rail is powered using a Denso DC Automotive Window Motor. The motor is controlled using a Talon SRX Motor Controller which the ESP32 controls sends PWM commands for speed and direction.

2.2.6 | Magnetic Power Switch

The boat currently does not have an on/off switch, relying on manually plugging and unplugging its battery. The 2022-2023 team implemented a magnetic switch that could facilitate turning the boat on but was unable to toggle it back off. This design was scrapped due to electrical issues.

2.2.7 | External Indicator

Currently, the boat has two telltales which indicate the wind flow over either side of the wingsail. There is no physical indication of the location of the servos in the rudder or trim tab, nor is their status indicated in the application.

2.2.8 | Sensor/Boat Feedback

The boat has a few sensors used for feedback control. The main odometry sensor used is the Airmar 220WX Weatherstation which gives GPS, gyro, magnetometer, and anemometer data. The ballast has a potentiometer to read where it is on the rail. The main boat also has a stereo camera which is used for buoy detection. The wingsail has an encoder to read the angle of attack which controls the trim-tab angle.

2.3 | Software

The previous team's software utilized several separate nodes tasked with maintaining distinct parts of the SailBot's operation, the interconnection of which is shown in Figure 6. The robot is controlled with a multiplatform application presented in Figures 7 through 9.

2.3.1 | ROS2

The previous team utilized ROS2, Humble Hawksbill, for their inter-robot communication. They divided the core functionality of the robot's operation between 9 nodes, shown in the RQt graph below.

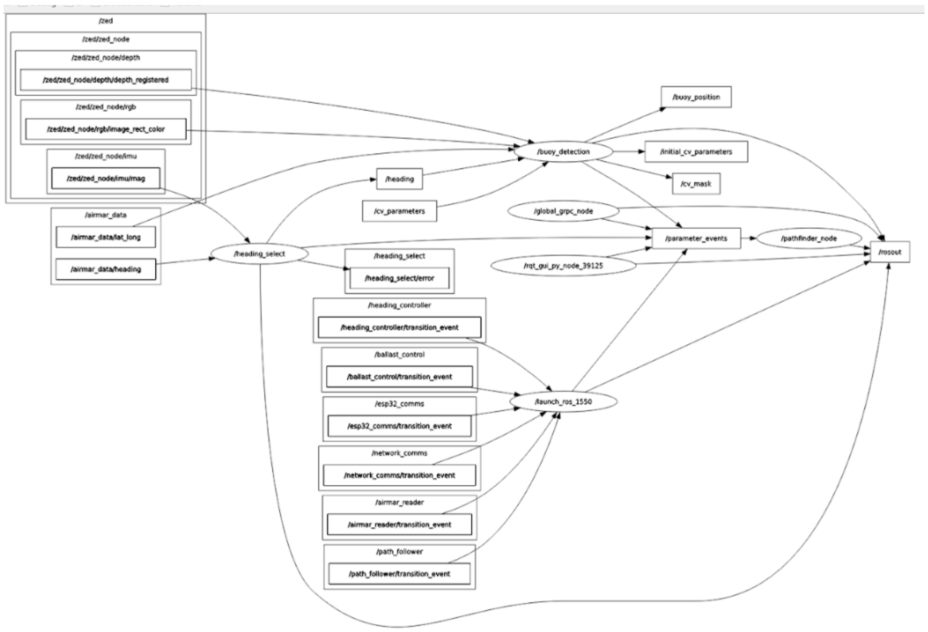

Figure 7: RQt graph of node interactions

These nodes include:

1. airmar_reader: Gathers information from the Airmar 220WX Weatherstation.
2. ballast_control: Controls the position of the movable ballast, when it is installed.
3. bouy_detection: Identifies buoys with the ZED2 camera and a CV algorithm
4. esp32_comms: Communicates between the Jetson Nano Orein in the hull and the ESP32 which handles sail sensors and motors.
5. heading_controller: Controls the movement of the rudder using instructions from the path_follower.
6. network_comms: Provides an interface to gRPC for the telemetry client application.
7. path_follower:
8. pathfinder_node: Using A-star, generates a navigable set of waypoints to a set target.
9. state_manager: Manages the states and operation of other nodes

2.3.2 | Computer Vision

The computer vision is stereoscopic using a StereoLabs Zed 2 camera mounted in an elevated position at the bow of the boat. It implements HSV image segmentation to identify buoys of known colors.

Control Application

The robot is controlled by an external, multi-platform, application built using Flutter in the DART language. The application consists of a main screen and two side panels which can be toggled open. The main screen provides a map of the body of water the SailBot is in with a continuously updated marker for the boat. The heading and trim tab angle of the boat can be manually controlled with two widgets at the bottom of the screen or set to one of a variety of autonomous or partially autonomous modes, including auto trimtab, auto rudder, and full autonomy.

Figure 8: Main screen of the telemetry application.

A side panel, pictured in Figure 10, opens on the left side of the application and provides a dropdown of all the launch files loaded onto the robot and, once one is selected, will show the status of each node in addition to a scrollable widget of their terminal outputs.

Opening on the right of the application is a settings tab, pictured in Figure 9. Within this panel is a variety of settings to fine-tune the autonomy of the robot, including Rudder Overshoot Bais, adjustment scale, and VF forward magnitude.

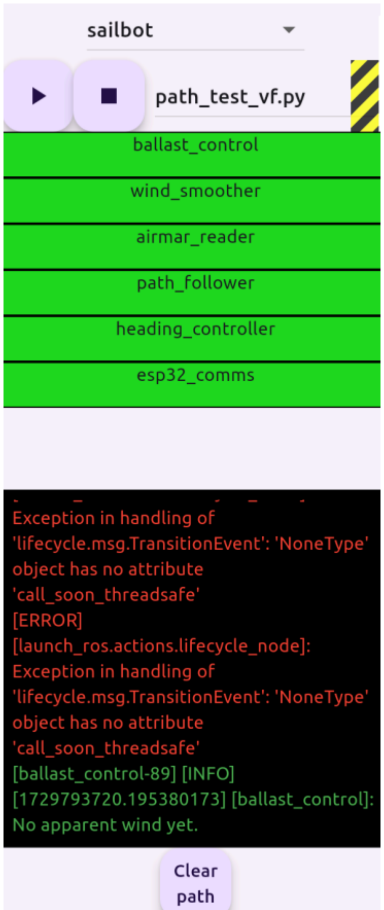

Figure 10: Node menu of the telemetry application.

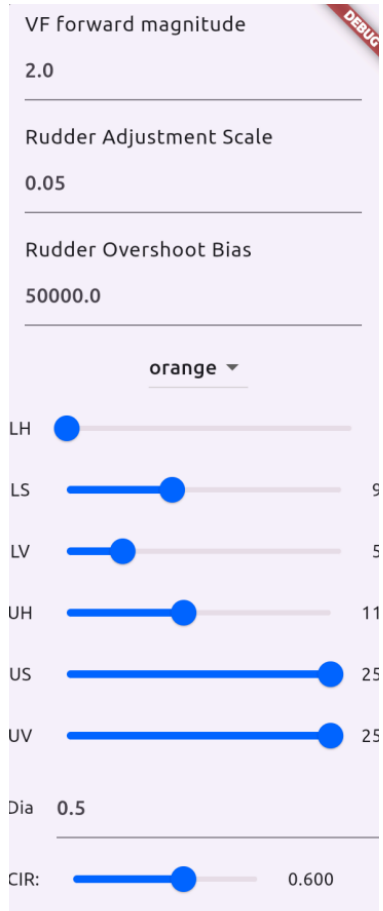

Figure 9: Settings menu of the telemetry application.

2.3.3 | Navigation

For planning a path autonomously, Sailbot relies upon PRM*, a probabilistic road mapping algorithm, although A* is also implemented. The A* algorithm first rotates the map so that the direction of the wind is at the top, then charts its path using a 7-neighbor approach, removing the direction of the wind as a navigable option. It is also modified to be rewarded for reaching the target point in as few tacks as possible. The PRM* is not based on a grid, instead opting to sample points on the map, and then create a path between these points to achieve the goal. This technique allows for greater sampling density to be focused on key features, such as buoys or obstacles, while plotting between less frequent points in open stretches. It is similarly rewarded for avoiding unnecessary tacks.

2.3.4 | Autonomy

Once a path has been generated, the boat is capable of following it with two different methods. The first is by using a look ahead algorithm, which picks points along the planned route in front of the boat and adjusts the heading by actuating the rudders and trimtab to target that point. This allows the boat to soften harsh turns or variations in its path but also means that the boat will cut corners, which can be problematic when navigating around buoys. The second strategy generates a vector field. This works by always pushing the boat towards the line and forward, meaning that it will attempt to follow the path exactly. This method introduces its own issues, namely that when taking sharp corners or switching directions too often the boat will overshoot before correcting and can potentially lead to snapping the rudder to extremes to try to compensate.

The rudder is used to control the boat's heading while the trim tab is used to adjust the wingsail. The rudder is controlled using a fuzzy logic controller which takes in the boat heading and angular velocity. The trim tab is controlled using state-based code which takes in the wind heading from the encoder and moves the servo. The states change the trim tab to cause the wingsail to be in maximum/minimum drag or lift for both the starboard and port side.

2.4 | Objectives

The boat is in a well-functioning state after winning the competition last year, so the main goals of our project are to improve the reliability and handling of the boat, as well as making it easier to operate and maintain. Additionally, we plan to implement more robust and dynamic software and ways to collect more data on the boat's operation. Below is our table of objectives.

Table 1: Objectives

Objective	*Benchmark*

Sail Redesign	• Outperforms current wing sail on a running point of sail based on:
	  ○ Angle between wind heading and boat heading
	  ○ Qualitative observations (sail and heading stability, keeping consistent speed, etc.)
	• Compatible with the current trim tab
	• Faster non-destructive access to the interior of the sail
	• No more than 10 percent heavier than the current design
	• Improved modularity
	  ○ Removable wind vane

Rotational Damping on Mast	• Implementing a viscous damping system connected to the mast and the hull. • Decreasing the oscillation amplitude of the wing sail when rocking the boat at 1 hertz to mimic ripples and wakes in water.
Increasing sail longevity	• Creating inspection sheets for each major component of the wingsail. • Building carrying cases for each part of the sail.
Rudder Rescaling	• Improved tacking and jibing performance. • Improved turning efficiency at slower speeds • Will work with the current linkage system.
Battery and Circuit Protection.	• Add current protection from overcurrent for 15A and battery life protection from undervoltage for 3V per cell.
Power Switch Assembly	• Ability to toggle the robot on and off without the necessity of plugging/unplugging the battery and without opening a hatch by using a magnetic switch. • This system should also not drain the battery or have any thermal problems.
Additional Sensors	• Read the current position of the trim-tab and rudders to increase feedback from the system. • *Reach: Add additional visual feedback in the boat via either main hull board or trim tab board*.
Improve object detection	• Reliable completion of Object Avoidance and Search tasks. This can be demonstrated with the successful completion of at least 4 out of 5 tests for both tasks. • *Reach: Complete Object Avoidance for objects without buoys*.
Reliability	• Autonomous completion of at least two laps on a 1+ mile round trip course and ending by passing through a gate of standard competition size. During this time the boat should round all marker buoys on the correct side.

3 | Design

3.1 | Mechanical

Several of the mechanical subsystems are iterations that were carried over from previous boats, such as the keel and rudders. The objectives on the mechanical side are largely to update these systems.

3.1.1 | Wingsail

To reiterate, the identified issues with the wingsail are transportation ruggedness, interior access, and point of sail range. These are not major issues, but not all of them are issues that can be solved without a major rework of the current design. To address these issues, our team will design and construct a new rigid wingsail to address these issues and leave the current assembly as is.

Although a major rework of the current assembly would be necessary to solve these problems, our new design is not a major redesign. The only problem that affects the performance of the boat is the point of sail range, which is the main issue that warrants a new sail rather than adjusting the current sail because it requires moving the mast further back in the sail.

The ability to sail downwind is a known issue with rigid wingsails (Silva et al., 2019). There are several reasons for this, but the aerodynamic forces play a part in it, especially for free-rotating wingsails like ours. The aerodynamic center of forces is where the resultant lift and drag forces act on an airfoil, and for most foils this falls at a quarter chord length from the leading edge (NASA). Currently, the mast is 4 inches from the leading edge of the foil, 2 inches forward of the aerodynamic center. This means that the mainsail lift creates a moment around the mast opposing the moment created by the trim tab lift, and for the wingsail to be held in static equilibrium, the moment about the mast must be 0. The simplified force diagram in Figure 11 shows an example of how the aerodynamic forces act on the assembly.

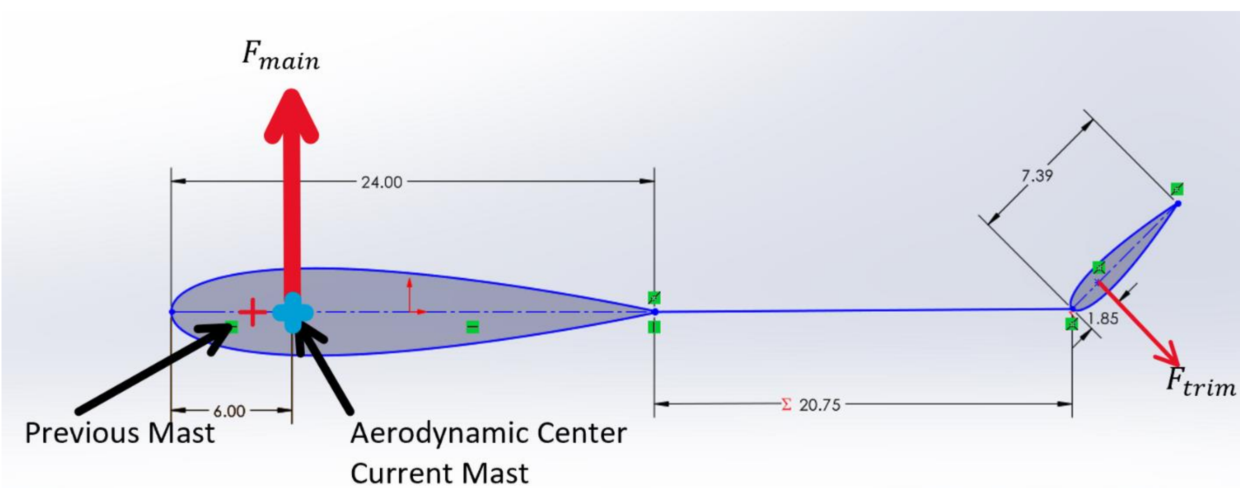

Figure 11: Diagram showing how aerodynamic forces act on the assembly

Most sailboats with free-rotating rigid wingsails put the mast at the aerodynamic center. Such as the Maribot Vane from the KTH Royal Institute of Technology and the unnamed boat recently developed at Laiocheng University (Tretow, 2017; Fang et al., 2024). Moving the mast to the aerodynamic center will greatly increase the trim tab's ability to control the rotation of the sail, since the mainsail lift will now act much closer to the mast and not influence the mast moment as much.

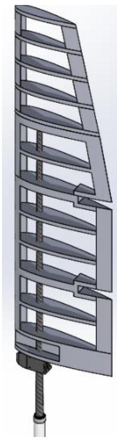

Figure 12: Preliminary CAD design on existing mast.

Figure 12 shows the preliminary CAD model for our design, assembled with the current mast for reference. This redesigned sail is essentially identical to the current design and will be made with the same materials (rigid foam, carbon fiber tubes, 3d printed connectors). Notable differences are the thicker rib at the bottom and the mast being moved back. The foil cross section is also NACA 0018 as opposed to NACA 0020. The measurements kept the same are:

- Rib thickness (except for the bottom rib)
- Trim tab boom spacing, in order to make it compatible with the current trim tab
- Leading and trailing edge thickness
- Chord length and tapering

The larger rib at the bottom will allow us to carve out space for the electronics and create an ergonomic cover that facilitates quick, non-destructive access to the interior of the sail. Additionally, we will make the wind vane removable and the trim tab booms more modular to help prevent damage to those appendages. Making the trim tabs more modular will also enable us to experiment with different boom lengths.

3.1.2 | Mast Rotational Damping

The original mast-to-hull connection provided no damping, allowing ripples and wakes to induce unwanted oscillations that compromised the stability of the wingsail. To address this issue, a viscous damping system was developed and integrated between the mast and the hull. This system is designed to absorb and dissipate energy from sudden rotational disturbances caused by small waves, thereby stabilizing the mast position. In addition to mitigating high-frequency oscillations, the damper also smooths out larger, intentional movements of the wingsail, improving control and responsiveness in variable water conditions.

A viscous damping system operates by using the resistance of a fluid, typically a thick oil, to absorb and dissipate kinetic energy. In our design, the mast serves as the moving component. As it rotates, it drives the damper gear, generating shear forces within the silicone oil. These shear forces resist the motion, creating a damping effect. The damping force in a viscous system is directly proportional to the velocity of the moving part; faster movement results in greater fluid resistance. This makes the system particularly effective at suppressing high-frequency oscillations caused by small waves and ripples.

Research was conducted on viscous damping systems to determine appropriate interior gap sizing, as well as on the design of custom involute gears using SolidWorks. The final configuration consists of two custom gears: one mounted directly onto the mast, and the other forming part of the damper assembly. The damper gear houses two 2-inch diameter ball bearings and an interior insert that creates a 0.05-inch annular gap between the inner diameter of the gear and the outer diameter of the insert. These dimensions were selected based on analysis of the redesigned wingsail model in SolidWorks. By selecting the correct materials used for the wingsail only, it was found to have a moment of inertia of approximately 1.11 $lb{\cdot}ft^2$ about its axis of rotation (the mast), indicating that only a modest damping torque is required to effectively reduce oscillations. Initial testing was conducted using 1000 centistoke silicone oil, comparable in viscosity to maple syrup, as a baseline. The entire damper system was designed to fit over the space previously occupied by the ballast system, eliminating the need for structural redesign. The system is shown in Figure 13 below.

Figure 13: Damper system attached to the vessel

3.1.3 | Rudders

To streamline testing, we 3D printed custom shells designed to slip over the existing rudders, allowing for quick installation and removal during validation without committing to permanent changes. The new rudders were created by uniformly scaling the original CAD model to preserve camber and foil shape. The span was then slightly shortened to ensure a secure fit over the existing rudders, and a cavity was formed by subtracting the original model from the new one. The fitment of the old rudder into the new is shown in Figure 14 below. The resulting model was split horizontally to produce two interlocking shell halves. This approach not only simplifies testing but also introduces design advantages:

- Increased leading-edge thickness shifts the axis of rotation closer to the hydrodynamic center, reducing the torque required from the servo.

A side-by-side comparison between the two pairs of rudders is displayed in Figure 15 below.

Figure 14: Old rudder fitment in the shell

Figure 15: Both rudders with new shells

3.2 | Electrical

The goal for electrical enhancements is to fix any issues with the previous boards and to add functionality to the boat.

3.2.1 | Additional Sensor Feedback & Status Indicator

An issue that the boat currently has is that it is not able to receive positional data from the trim tab and rudder servos. This means that the software knows the angle that the servos are set to but not where they currently are. To add the ability to read the current position of the trim-tab and rudders, the AGFRC IA73BHLW Waterproof Position Feedback Servo were bought. This servo is rated for 5V, 180 degrees of rotation, and gives a 300mV-3000mV signal for feedback.

The robot currently does not have any external indicators on it that show what state it is in. Previously, an E-Paper was used to show what the boat is currently doing but it was removed a couple of years ago. Although helpful, the use of external indicators for the boat isn't entirely needed as the application to the boat gives more information about the boat systems than a status light or E-Paper. Added to the application will be the ability to read the individual battery cells explained below.

3.2.2 | Fix Issues with Previous PCBs

Last year the team switched to having fully custom PCBs which mount many of the main electronics inside the hull and in the sail. One main issue with the previous main hull PCB is that the Battery Management System (BMS) explodes when powered. Another issue is that the magnetic power switch to turn the boat on/off was removed and replaced with the BMS, although it was designed with a magnetic latch in mind. Fixing the BMS was a large priority as before the boat was turned on/powered off by just unplugging a battery.

The new PCB features an upgraded BMS designed for a 4-cell LiPo battery. This board includes the BQ7790512 battery protection IC, a 5 V step-down regulator, ability to read individual cell voltages, and dedicated spots for additional sensors. The main controller is still the Jetson Orin Nano and the co-processor is an ESP32. Lastly, there are still headers and power to include a motorized system like the ballast, although it was removed this year to fit the mast damping system.

The BQ7790512 battery management IC monitors each LiPo cell for overvoltage, undervoltage, and overcurrent conditions. If any cell voltage falls outside the 2.8–4.175 V protection window, or if excessive current or a short circuit is detected via a high-precision shunt resistor, the BMS opens its discharge FET to isolate the load. In addition to the BMS, a mounting for a typical blade fuse is used in case of a short through the system, which allows for both additional protection and if the board is powered via a standard power supply. This design implements a protection and monitoring system for a 4S LiPo battery pack (16.8 V max, 14.8 V nominal) using the Texas Instruments BQ7790512 battery monitor IC:

Voltage Protection:

- OV threshold: 4.175 V per cell (16.7 V total)

- OV recovery: 3.975 V per cell
- UV threshold: 2.8 V per cell (11.2 V total)
- UV recovery: 3.0 V per cell (load removal required)

Current Protection:

- OCD1: 15.0 A (75 mV threshold), 1.42 s delay
- OCD2: 30.0 A (150 mV threshold), 350 ms delay
- SCD: 60.0 A (300 mV threshold), 1 s delay
- Recovery: Load removal + delay

Temperature Protection:

- Over-temperature discharge (OTD): 65 °C
- Under-temperature discharge (UTD): –20 °
- Over-temperature charge (OTC): 45 °C
- Under-temperature charge (UTC): 0 °C

Shown in Figure 16 is the current redesign for the BMS circuit. It is heavily based on the BQ77904/ BQ77905 datasheet instead of the circuit built last year. The CSD19534Q5A MOSFET Driver was chosen to meet the full battery supply requirements which can supply around 200A. The driver is rated for 100 V_{DS}, and 10A I_D. The BMS protects the battery from Under Voltage and Over Current. This is important as the battery can be damaged from overcurrent and will get damaged from the cells running low. This circuit also is designed to protect the rest of the electronics downstream from shorts as if the BMS or the fuse blows, there is no more connection with the rest of the electronics. In the case of BMS, it has its own ground which connects to the battery cell ground in JST connector and the Battery- lead. The system ground is connected after the discharge MOSFET which is the ground for the rest of the system. If the boat is powered off a wall DC power supply then a jumper can be used between both grounds which will bypass the BMS.

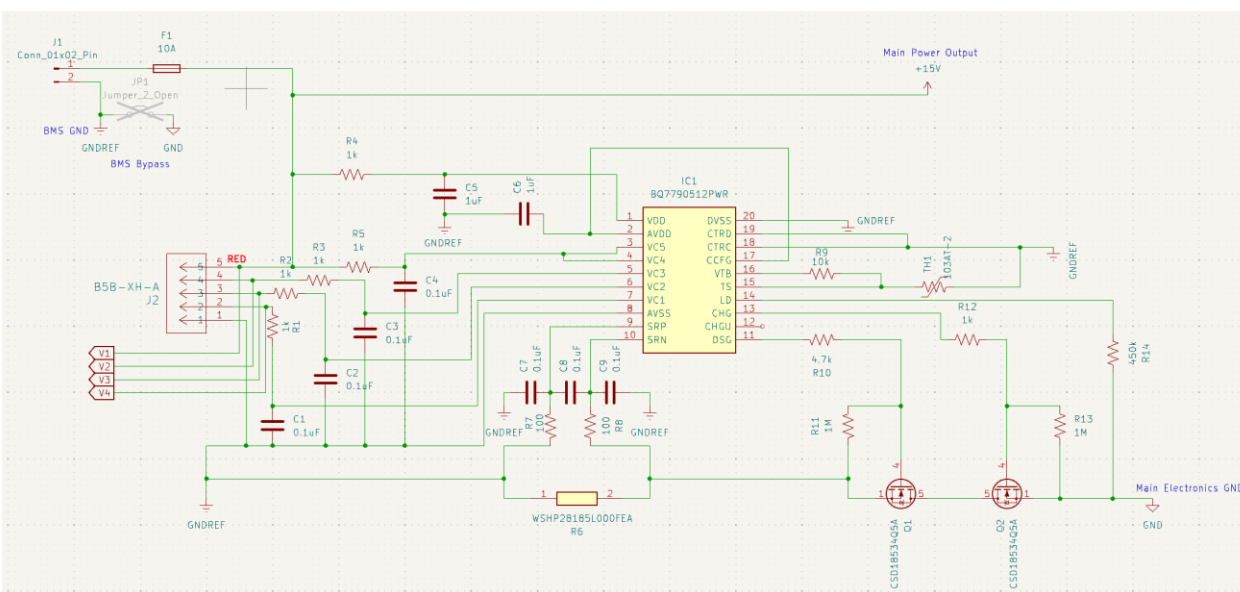

Figure 16: Redesigned BMS circuit diagram

Battery monitoring has been significantly improved by replacing the MCP3008 and MCP604 setup with a high-resolution ADS8638 ADC and a OPA4197 op-amp. Each of the four cell voltages from the JST balance connector is scaled down through matched resistor dividers and buffered with the op-amp before being read by the ADC. The ADS8638 is configured with a 5V analog supply and 3.3V digital supply to communicate to the Jetson over the SPI connection. Each cell value can be calculated using a combination of the previous cell ADC value and the voltage divider scalar. For any 5V logic devices, there is a 5V DC-DC converter. The TPS54560BDDA buck converter provides up to 5A at 5V. For 3.3V output, the Jetson has a 3.3V supply. As another option for 5V output, a jumper is available between the 5V rail and the Jetson 5V supply.

3.3 | Software

Software changes focused on increasing reliability of the SailBot as well as adding functionality for more IRSR tasks. These changes included optimization of computer vision, removing bugs, and adding simulation capabilities.

3.3.1 | Improved computer vision

In its past state, the computational load of the object detection system could be extreme, leading to considerably delayed detection and occasional crashes of the client-side telemetry application. This caused issues during the 2024 competition as inaccuracy led to passing on the wrong side of or entirely missing gates and buoys. The robot's camera was operating at 30 fps, with Full HD (1920 x 1080) resolution. Images from the camera, either raw or processed depending on settings, were converted to messages through the *cv2_to_imgmsg* function and sent in their entirety to the telemetry application for viewing. We sought to reduce overhead in this process by lowering framerate and resolution of the camera's images before processing begins, and substantially reducing the size of images sent to the telemetry application. This has allowed for preservation of accuracy on the robot side while mitigating network strain.

In the event that the robot accidentally crosses on the wrong side of a buoy, which can be caused by buoy location deviation or other unexpected factors, its passing would not be registered, per competition rules. In the previous year this requirement was removed as boats were struggling to consistently round buoys, but this cannot be assumed for future competitions. Fail safes were implemented in the case that a buoy was not within a given distance of its expected position. The waypoint being used to navigate will first snap to align with the buoy then path generation will be retriggered to correct the path. Path generation can be computationally expensive and take up to a few seconds, but with the speed the boat is travelling this was deemed acceptable.

Bouy detection has also been an issue when the boat is required to navigate between a two-buoy gate, as is the case in the Precision Navigation task. The boat will currently generate a path as if it is rounding one of the buoys and make the radius half that of the distance between the two to pass between them, then generate a path to a point on the far side of the gate to maintain a straighter heading. This has also been affected by the above changes, allowing the boat to fine tune its path during the approach.

3.3.2 | Bug Fixes

Another issue identified during the 2024 competition is that the telemetry application designed to monitor and control the boat would crash or lose connection. This was suspected to be due to a resource leak in the communication between the application and the main boat. It was proposed by Matthew Gomes, a member of the 2023-2024 SailBot team, that the issue may relate to the system generating new connections in the event of a connection loss and reconnection. During investigation of this issue it was discovered that the leak was fully on the telemetry application side. The widget which displayed the camera feed was overwritten each frame, but its cache was not correctly deleted, leading to slowdowns and freezes if it was run too long. Once the issue was located it was a quick fix, and operation has been much smoother since.

To resolve the problem with network connection the team has switched our network manager from using Zero Tier to Tail Scale. Zero Tier's free service, which was being used by past teams, is being depreciated by the company. It encountered frequent connection issues, far fewer of which have been noted since the swap to Tail Scale.

3.3.3 | Controller support

The telemetry application designed by the previous team provides a vital service, allowing the boat to be monitored and controlled from afar. In the current implementation of the application, direct control of the boat is exercised through two widgets on the bottom of the screen, which can be pulled left or right to adjust the angle of either the rudder or trimtab respectively. Although this method does work, using touch controls on a phone lacks any haptic feedback, meaning that the operator often must look down to ensure they are inputting the correct commands, momentarily preventing them from monitoring the state of the physical robot. This can result in over-correction and inconsistent travel.

A controller has been implemented to operate alongside the application, interfacing with the boat through its cellular connection. The controller has direct control of the rudder and trim tab with joysticks, as well as the ability to lock them at a certain angle to maintain consistent movement. The controller has buttons that are mapped to the various states of autonomy the boat possesses, allowing switching between them to be simple and fast. Allowing the boat to be operated with a controller should make it feel more intuitive to operate and lessen the need to split the operator's attention while sailing.

3.3.4 | Simulation

As it is necessary to test the boat outside on a body of water, it has proved difficult in past years to test the code during the winter. To help with this issue, simulation features have been added to the existing telemetry application. This includes the ability to move waypoints and create fake buoy detections which will continually pulse their location as if seen by the camera. Visual indicators have also been added to show the radius of important features, such as reliable vision distance and snapping points of buoys.

3.3.5 | Update to accommodate hardware changes

In addition to the above modifications and improvements to the legacy codebase, updates were made as necessitated by other mechanical or electrical works done this year. This includes modifying sailing parameters to account for a moved sail and tuned rudder control.

4 | Systems Testing and Validation

Table 2: Validation

Objective	*Status*	*Validation*
Sail Redesign	Met	Outperforms current wing sail on a running point of sail based on: • Angle between wind heading and boat heading • Qualitative observations (sail and heading stability, keeping consistent speed, etc.
	Met	Compatible with the current trim tab
	Met	Faster non-destructive access to the interior of the sail
	Partially met	No more than 10 percent heavier than the current design
	Partially met	Improved modularity • Removable wind vane
Damping System	Met	• Effectively reduced amplitude of motion of the wingsail during a manual test while the damper system was engaged.
Rudder Remodel	Partially Met	• Outperforms old rudders based on flow simulations in SolidWorks. were conducted on both old and new rudder geometries at different angles of attack (0°, 5°, 10°, 15°).
Increasing sail longevity	Partially Met	• Sheets have been created and used whenever the sail has been transported.
Battery and Circuit Protection.	Partially Met	• An analysis of the circuit has been made to ensure the battery and board is protected from overcurrent from use of a separate system ground. • The BMS protects the battery against under-voltage from use under 2.8V and recovers at 3V. ○ The full PCB will be fully validated before the 2025 Competition
Power Switch Assembly	Unmet	• Due to focus being put on creating the Main Hull PCB, this task was not accomplished.
Additional Sensors	Partially Met	• The AGFRC IA73BHLW Position Feedback Servo is able to be written towards an angle based on the current PCB. • The positional feedback is able to be read based on a separate ESP32 test board.
Improve object detection	Partially Met	• Simulations of the search and rescue task have been conducted, but extensive water tests are still needed.

		• Path correction has been observed when buoys shift location in simulation. • Frame rate of streamed video feed on telemetry application has increased.
Reliability	Partially Met	• New network manager software has proved far more consistent in holding connection. • Telemetry application no longer experiences crashes due to memory overflow. • Long distance sailing test has yet to be completed

Table 3: Validation (continued)

4.1 | Mechanical

4.1.1 | Wingsail

The frame of the wingsail was made out of rigid foam insulation board and mounted on a carbon fiber windsurfing mast with the help of 3D printed adapters. The foam pieces were machined using CNC, glued together, sanded, painted with acrylic paint, and the trailing edge was epoxied to protect the areas of the wing prone to wear. The frame was then covered with ultracote, a heat activated adhesive wrap. For photos of the construction process, refer to Appendix C.

The two wingsails were tested in the lab by placing the hull on supporting foam pieces to hold it stationary and pointing a fan at the assembly. This allows us to isolate the wingsail assembly while still using it in conjunction with the hull as it is designed to be. The wingsail was angled perpendicular to the fan and then allowed to rotate on its own until it stopped.

This test was repeated twice and yielded similar results both times, showing a visibly noticeable 5-10 degree difference in angle. The new wingsail was closer to perpendicular with the wind both times. Figure 19 and Figure 20 show the initial test, without any measurements being taken. **Error! Reference source not found.** and **Error! Reference source not found.** show the

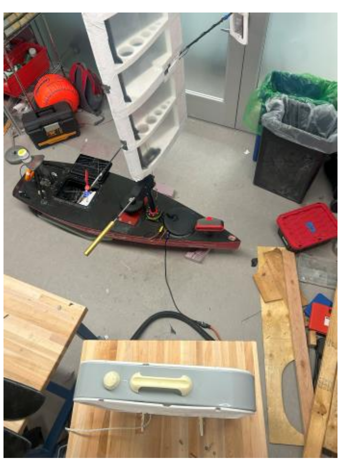

Figure 20: 1st test of old wingsail

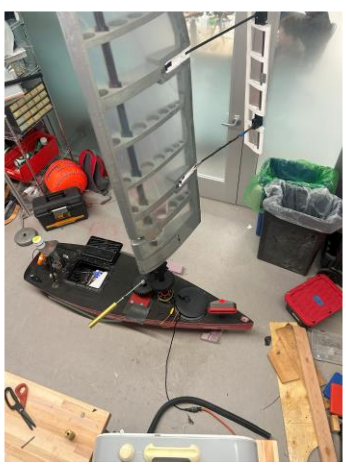

Figure 19: 1st test of new wingsail

Figure 17: 2nd test of new wingsail

Figure 18: 2nd test of new wingsail (cont.)

results of the second test after marking the position of the old wingsail with yellow tape. All these photos were taken while the fan was on.

4.1.2 | Damping System

To evaluate the effectiveness of the viscous damping system, a rocking test was performed with the mast and wingsail assembly at approximately 1 Hz representing the frequency of oscillations caused by small waves and wakes. The system was tested in both engaged and disengaged states, with motion recorded from a top-down perspective. At the point of maximum amplitude in each test, images were captured and overlaid to visualize the difference in rotational displacement in Figure 21 below.

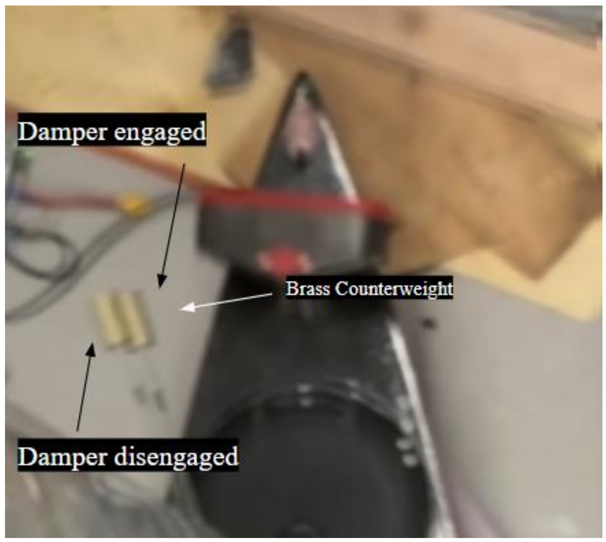

Figure 21: Overlay of sail rotation with and without the damper engaged during rocking test.

The position of the brass counterweight highlights the difference in maximum rotational displacement: greater movement is observed when the damping system is disengaged, confirming its effectiveness in reducing oscillation amplitude. While the reduction was modest, the test demonstrates that the damper provides measurable resistance to motion. This baseline evaluation, conducted with 1000 centistoke silicone oil, suggests that higher-viscosity fluids may further enhance damping performance. To maintain consistency between trials, a 60 BPM metronome was used to time the rocking motion at approximately 1 Hz, and ground markers were placed to guide the amplitude of each cycle. While the setup was manual, these controls helped ensure the input conditions were as consistent as possible. Future testing with a motorized fixture or instrumented setup is recommended to produce more precise and repeatable data.

4.1.3 | Rudder Remodel

To validate the performance of the redesigned rudders, a series of comparative flow simulations were conducted in SolidWorks. Both the original and new rudder geometries were tested at angles of attack in 5° increments ranging from 0° to 15°. Each simulation modeled steady-state water flow at 1 m/s and recorded the resulting lift and drag forces on the rudder surfaces. The goal was to assess differences in turning authority, drag, and overall hydrodynamic efficiency between the two designs. The new rudders, which feature a longer chord and slightly reduced span, were expected to improve the lift at low speeds. The lift and values used in Figures 22–23 was taken from a comparative flow simulation dataset compiled in *Rudder_FlowSimulation_Data.xlsx* (see Appendix 8.4).

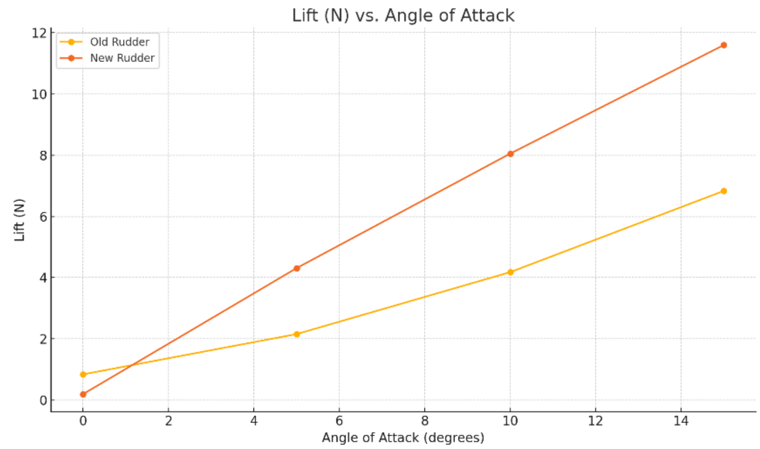

Figure 22 21: Lift vs. Angle of Attack

This figure compares the lift produced by the old and new rudder designs across a range of angles of attack. The old rudder appears to generate more lift at 0°, this can be caused by small asymmetries in the original model and the meshing density of the flow simulation. The new rudder significantly outperforms it at higher angles, however, from 5° and 15°. This indicates improved turning authority and responsiveness during active steering with the new design.

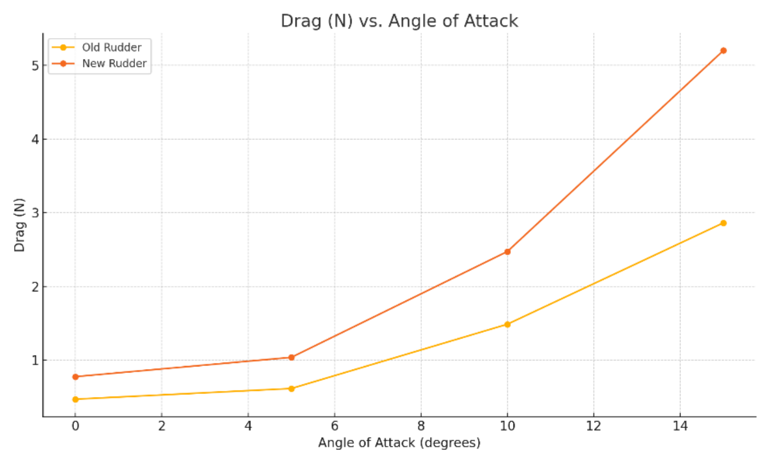

Figure 23 22: Drag vs. Angle of Attack

This figure shows the drag produced by each rudder. As expected, the new rudder generates more drag across all angles of attack due to its larger surface area, chord, and profile. However, this increase in drag is offset by the substantial gains in lift, especially during larger rudder deflections.

4.1.4 | Sail Longevity Additions

As part of the effort to ensure the long-term durability of the wingsail, inspection sheets were created for each major component of the assembly (figure 24 below). These sheets included diagrams and designated spaces to record observations related to surface damage. The team was able to use the sheets when transporting, which enabled early identification of minor issues and helped with maintenance decisions. Although custom carrying cases were planned to protect the wingsail during transport, the team was unable to fabricate them due to scheduling issues and the capacities of the group's vehicles, which should have been considered during initial planning. Despite this, the successful use of the inspection sheets represented a meaningful step toward extending the operational life of the wingsail.

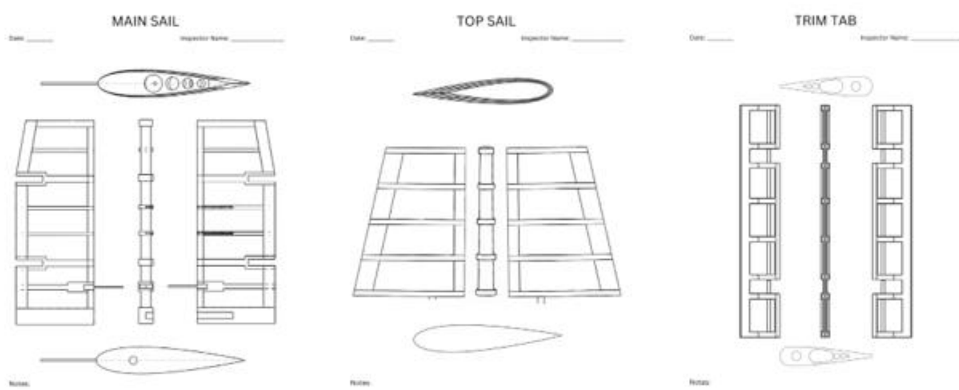

Figure 24: Main, Top, Trim Tab sheets

4.2 | Electrical

4.2.1 | BMS Calculations

Below are the calculations for the RC time constant approximation using the CSD18534Q5A MOSFET and resistor values for charge and discharge gates.

Gate Drive Timing and Protection Threshold Calculations:

The following calculations validate the gate drive timing for the CSD18534Q5A MOSFETs used in the charge (CHG) and discharge (DSG) paths, as well as the overcurrent protection thresholds based on the chosen current-sense resistor.

RC Time Constant Approximation:

$$\tau = R_g \times C_{iss}$$

Where:

- C_{iss} – Input capacitance of the MOSFET
- R_g – Gate resistor value

For the CSD18534Q5A:

Ciss = 1360 pF (typical), 1770 pF (max)

Discharge Path (DSG) — R_{DSG}= 4.7 kΩ

- τ = 4700 Ω × 1360 pF = 6.39 µs (typical)
- τ = 4700 Ω × 1770 pF = 8.32 µs (maximum)

Charge Path (CHG) — R_CHG = 1.0 kΩ

- τ = 1000 Ω × 1360 pF = 1.36 µs (typical)
- τ = 1000 Ω × 1770 pF = 1.77 µs (maximum)

These results confirm that both charge and discharge MOSFETs will switch within microseconds which are well within safe response timing for the BMS gate drivers.

Shown below under table 3 are the Overcurrent Trip Current Calculations The system uses the WSHP28185L000FEA shunt resistor:

- Resistance: 5 mΩ
- Power Rating: 10W

Table 4: Overcurrent Trip Current Calculations

Protection Mode	Trip Voltage	Calculated Trip Current
OCD1 (mild overload)	75mV	75 mV / 5 mΩ = **15 A**
OCD2 (moderate OC)	150 mV	150 mV / 5 mΩ = **30 A**
SCD (short-circuit)	300 mV	300 mV / 5 mΩ = **60 A**

4.2.2 | ADC Calculations

The Jetson Orin Nano takes 3.3V logic through its header pins so the previous MCP3008 ADC could not be used under 5V. This would mean the cell voltages would have to be taken down to 3.3V maximum or another ADC IC is used. The ADS8638 ADC can have separate AVDD and DVDD for 5V analog in and 3.3V analog out, powered from 3.3V rail on the Jetson. The full ADC circuit schematic can be seen in Figure 25, which shows the voltage divider for each cell. To be able to read the cell voltages, they are each brought down to a maximum of 5V (V1 16.8V at full). Table 4 shows how to calculate each cell voltage once the data gets passed into the Jetson.

Table 5: Individual Cell Voltage Calculation

Cell	**R1**	**R2**	**Divider Ratio k**	**Formula**
V4	None	None	1.000	V4 = V4
V3	6.8kΩ	10kΩ	0.595	V3 = V3/0.595 - V4
V2	16kΩ	10kΩ	0.385	V2 = V2/0.385 - V3
V1	24kΩ	10kΩ	0.294	V1 = V1/0.294-V2

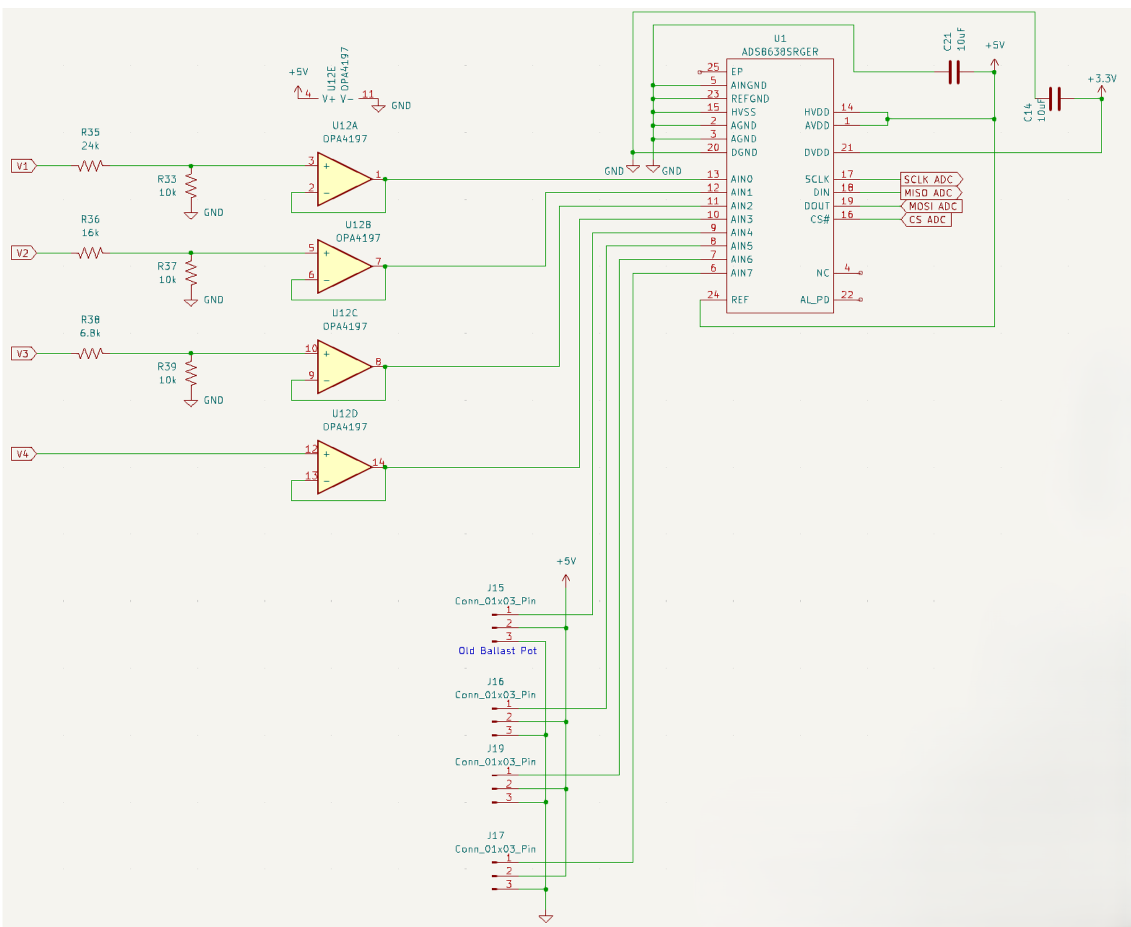

Figure 25: Schematic of ADC Circuit

4.2.1 | Physical Testing

The PCB will be tested for each of the following parameters once ordered:

- Overcurrent detection by adding a load through the circuit and measure the circuit to verify it trips at set current threshold.
- Undervoltage detection by adding simulated LiPo battery at different cell voltage inputs, measuring the circuit to verify that it trips when cells are under 3V.
- Simulate Endurance Event by powering the boat for at least 7h and measure the remaining battery capacity at the end of the test.
    - To simulate camera and rudder usage, we will drive both the rudder and use the camera based on sim data before testing it out on the water.

Since the Magnetic Battery Switch was not able to get ordered or made, these are the parameters to test:

- Measure the current while the switch is plugged in both off and on.
    - There should be no current measured when the switch is off
- Validate the switch system by switching it on/off using a magnet for extended periods of time.
- Simulate Endurance Event by leaving the boat on for at least 7h and measure the heat generated from the switch.
- Test resettable breaker by drawing more than 20A through the circuit to cause a break.

4.3 | Programming

4.3.1 | Improved Object Detection

Optimizations for object detection can be verified by monitoring the frame rate of the streamed video on the telemetry application. The video is still delayed by approximately 2 seconds, which has decreased from the 5 seconds noted during our benchmark testing.

Buoy navigation and search abilities were demonstrated first in the lab by moving buoys around the stationary boat while it attempts to track and adjust heading based off their movements. For the search and rescue task, simulations have been run to demonstrate the boat can consistently find and hit the buoy within the 10-minute timeframe.

4.3.2 | Bug Fixes

Since updating the telemetry application to clear the memory cache it has not encountered the issue again. Tail Scale has also proven to be consistent and held connection through a variety of settings, with Wi-Fi, ethernet and cellular.

4.3.3 | Controller Support

Implementation of controller support has been demonstrated through the usage of the controller for the teleoperation of the robot. This included sail and rudder control, locking and unlocking controls, and changing the autonomy state of the robot. Controller support is togglable from within the application.

4.3.4 | Simulation

Operation of the search and rescue task has been consistently completed in simulation. In addition, the boat has correctly recognized issues and replanned its path based off changes made during its navigation.

5 | Analysis and Discussion

5.1 | Mechanical

5.1.1 | Wingsail

The first two tests were promising and the new wingsail performed as desired, but these tests were far from perfect. Improper weight balance and fit to the mounting were the biggest issues. The mass of the counterweight was reduced to better balance the new assembly, and we were only able to fit one shim in due to the shims being a bit too thick for the new mast.

This definitely affected the test, but it's reasonable to assume that improvements to the balance and fit of the assembly will only improve upon the results shown in these first two tests. The fact that it doesn't seem to need as much weight to balance it could even end up making the new assembly even lighter than the current one. While electronic parts have not been put into the wingsail yet due to order delays, the trim tab does fit into it, and the new compartment fits the current electronics box.

5.1.2 | Damping System

Testing of the damping system revealed that even with low-viscosity 1000 cSt silicone oil, the damper effectively reduced wingsail oscillations during a 1 Hz rocking test. While the reduction in amplitude was modest, it confirmed that the system introduces measurable resistance to rotational motion. This outcome aligns with expectations given the fluid's viscosity, the relatively small contact area, and the 0.05-inch gap used in the damper. The fact that a difference was observed validates the design approach and suggests that damping performance could be further improved by using a higher-viscosity fluid, increasing the shearing surface area, or narrowing the fluid gap. The modular design allows for easy fluid replacement, enabling future tuning without structural changes. Overall, the damper serves as a promising first implementation of passive rotational stabilization, helping to reduce unwanted motion without relying on active control systems

5.1.3 | Rudder Remodel

The redesigned rudders show a clear improvement in performance over the original configuration based on flow simulation results. By increasing the chord length and slightly reducing the span, the new design achieved significantly greater lift at all deflected angles, particularly at 10° and 15°, where control authority is most critical. Although the drag also increased due to the larger surface area, the trade-off was justified by the substantial gains in turning force. At 0°, the original suggesting better efficiency during straight-line tracking due to its lesser surface area and dimensions. However, the new rudder outperformed the original at 5° through 15° and maintained comparable efficiency at higher angles, indicating improved responsiveness during active maneuvers. These results validate the design changes and confirm that the updated rudder geometry provides enhanced hydrodynamic performance in conditions where steering input is required most.

5.1.4 | Sail Longevity

The use of inspection sheets throughout testing proved to be an effective method for documenting wear and ensuring the structural integrity of the wingsail over time. This low-cost, manual tracking approach helped the team build a consistent maintenance routine and identify potential failure points before they become critical. Although the transport solution was not completed, this choice allowed the team to focus its efforts on the wingsail's core mechanical systems. The inspection process itself can serve as a useful foundation for long-term maintenance practices in future iterations of the project.

5.2 | Electrical

5.2.1 | New Hull PCB

Based on the analysis, the BMS circuit should be able to protect the electronics and the battery from damage. The PCB was not created in time to be ordered for physical testing. However, it will be able to be ordered before the competition in June.

5.3 | Software

The increased reliability of the boat's connection made the experience of working with the boat both inside and outside of the lab considerably less frustrating. At the beginning of the year, we had several issues with connection suddenly cutting out or the network manager on the boat just turning itself off, which seem to be resolved. It should be noted that there is a team Tail Scale admin page which is where you must register a device for it to be visible to the sailbot and vice versa. Ownership of this will be passed down to future teams.

A lot of the changes made in software this year are not detectable in the robot's operation, namely a bunch of cleanup and formatting. Unfortunately, a lack of availability for the team to complete water tests made the testing of software changes challenging this year. This was offset in part by the increased simulation capabilities but, as any coder knows, seeing something work in simulation is far from a guarantee it will work in actuality. They should be prioritized and planned far in advance by future teams.

6 | Conclusions and Recommendations

6.1 | Mechanical

6.1.1 | Wingsail

While the wingsail still needs a fair bit of work before it's usable in competition, it does meet a majority of the predefined standards. The most important one, trim tab authority over the angle of attack, was tested successfully in the lab, and the difference should be improved with further work on the sail. It's compatible with all parts of the current assembly being carried over, which are the sail electronics box and trim tab. Although it hasn't been properly weighed, there isn't any noticeable difference, and the new wingsail might even end up being lighter if the mass of the counterweight can be reduced.

As is, it could be used in the fleet race under manual control once the weight balance and mounting assembly issues are fixed. Before it can be used autonomously a new windvane needs to be built. Additionally, the trim tab and topsails should both be rebuilt. While it's still usable, both the trim tab boom and ribs have been broken. The topsail is a lower priority, it's just that the craftmanship was a bit poor given that it was the first piece of the sail constructed. If there's extra time, future teams could build extra trim tab booms of varying lengths.

In the future, teams ought to focus on creating a dependable transport system for the wingsail to reduce damage during handling and storage. A portable or foldable carrying case, possibly made from lightweight composite materials or cushioned fabric, would safeguard the sail from damage and weathering while keeping bulk to a minimum. Incorporating these practices into regular sail handling and deployment will aid in maintaining structural integrity during future competitions and testing phases.

6.1.2 | Damping System

The damping system effectively showed its capability to decrease wingsail oscillations through a viscous damping mechanism. Despite utilizing a low-viscosity oil (1000 cSt), the system demonstrated quantifiable resistance to movement during testing, confirming the idea as an effective approach for passive stabilization. To enhance performance even more, upcoming teams are encouraged to test higher-viscosity silicone oils, as it is expected to deliver increased damping torque and better control. Moreover, upcoming testing should focus on adopting a more controlled and reproducible approach rather than manually rocking the vessel, such as utilizing a pendulum-type set up to more accurately measure damping effects. These actions will enable enhanced precision in adjusting and assessing the system's performance with the different viscosity oils.

6.1.3 | Rudders

The redesigned rudders showed considerable advancements in lift and hydrodynamic efficiency during simulated scenarios, especially at moderate to high attack angles. Through the extension of the chord length and refinement of the geometry, the updated design attained enhanced lift and an improved lift-to-drag ratio in areas where active steering is critical. These outcomes confirm the design modifications and reinforce the objective of improving low-speed handling and turning capability. With a greater surface area, the new rudders also brought increased drag, especially at a 0° angle of attack, potentially impacting straight-line efficiency. Upcoming teams could explore experimenting with different foil shapes to minimize drag at shallow angles while preserving lift at steeper angles. It is also encouraged to conduct physical in-water tests as much as possible to confirm the simulated outcomes and evaluate actual steering responsiveness in varying flow situations.

6.1.4 | Other Improvements

At the beginning of the year, when deciding what to do about the defunct sliding rail ballast system, the possibility of other stabilization systems was discussed. Some of the systems explored were hydrofoils, angled amas (extra hulls), and integrated control surfaces on the keel. If designed well, a new system such as one of these could greatly improve our control over the boat. The keel, while perfectly functional, was designed for a different hull so this is another physical part that could stand to be replaced. The securing bolt also can't go all the way into the keel, so the mounting mechanism has some room for improvement.

6.2 | Electrical

Overall, the Main Hull PCB took up more time than expected, which didn't allow for fully completing all of the tasks. This along with learning how to create a PCB from scratch is not entirely recommended and for future groups it would be best to have someone who knows how to make a PCB beforehand.

6.2.1 | Magnetic Power Switch

The magnetic switch was part of the original objectives which did not get done as the Main Hull PCB was put first. Further recommendations would be to make sure that if the switch breaks the connection between the main battery lead, the JST connector should also be cut to not use up unneeded power for the BMS.

6.2.2 | Closed Loop Control

Control trim-tab and rudders via closed loop control can be added once the AGFRC feedback servo is in use. This would allow for more accurate control of the systems instead of using a FUZZY logic controller for the rudders.

6.2.3 | Trim-Tab PCB Changes

The 5V-3.3V Logic converter circuit currently is not being used as it is replaced with a voltage divider leading straight into the ESP32. Another issue with this PCB is that currently an external 5V power bank is used as the 3.7V LiPo booster has been failing to power both the board and the servo/encoder.

6.3 | Software

6.3.1 | Improved Object Detection

It was discussed this year whether the use of artificial intelligence would be beneficial in object detection, though the idea was eventually abandoned due to lack of training data and computational power. The Jetson Orin Nano used in the Sailbot has a built in GPU which, in theory, would make it capable of efficient detection. Taking on AI based computer vision is a massive commitment of time and resources, which is one of the main reasons that it was abandoned this year and has not been successful in the past.

6.3.2 | New Tasks

The code is in a functional state, and that provides the perfect base to add functionality for more tasks. The object avoidance task could be greatly improved upon, and there are plans to attempt to have it working by competition this year. Even if it does function it will definitely need improvement by future teams to optimize the path planning, as the current version is just to see what direction the obstacle is going and place a waypoint behind it, which does not take into account the movements speeds or distances of the boats.

6.3.3 | Simulation

Adding more features to the telemetry apps simulation side could be very helpful for testing software quickly without the need to run the boat on real water. The current features are based solely around path planning and navigation, but this could be expanded to simulate features such as shifting wind or to allow for speeding up and slowing down of the simulation dynamically. The object avoidance task has also not been simulated yet.

7 | References

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8 | Appendices

8.1 | Appendix A: Sailing Basics (Direct excerpt from SailGoat: Autonomous Sailing System 2021-2022, Del Vecchio et al., 2022)

2 Background

In this section we introduce the topics critical to understanding the Sailbot project. Sailbot is a robotic sailboat, and thus it is important to have a basic understanding of both sailing a traditional sailboat and a robotic one. Additionally, this section introduces the International Robotic Sailing Regatta (IRSR) rules and challenges. Finally, the states of the mechanical, electrical, and software systems of the vessel as left by the 2020-2021 Sailbot team are discussed.

2.1 Sailing Basics

A general understanding of the terminologies and concepts of traditional sailing are crucial to the development and optimization of a robotic sailboat. The four areas of importance are: general terminology of sailboats, points of sail, tacking and jibing, and rights of way.

2.1.1 General Terminology

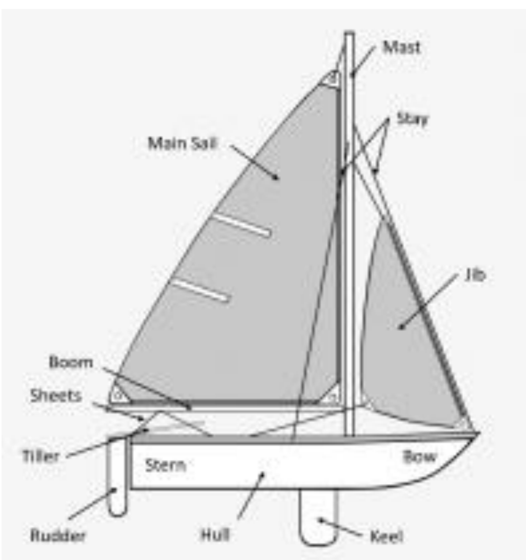


Figure 1: Anatomy of a typical sailboat

The terminology and function of each part/system in the boat are valuable to understanding how to develop and control a boat. A typical sloop rig sailboat is shown in Figure 1 with all the major components and systems labeled. Figure 2 illustrates the pre-existing components and systems on Sailbot as left by the previous team. The primary structural body of a sailboat is the hull, to which all other systems are attached. Attached to the bottom of the hull is the keel, a fixed underwater wing used to prevent sideways drift and provide stability. Note the difference in keel shape from the traditional sailboat (Figure 1) to Sailbot (Figure 2); Sailbot's keel has a bulb at the end. The rudder is the sailboat’s moveable underwater steering mechanism. In a traditional sailboat, the tiller, a wooden or metal beam, is used to turn the rudder, as seen in Figure 1. Typically, sailboats

2.1.2 Sailing Basics 3

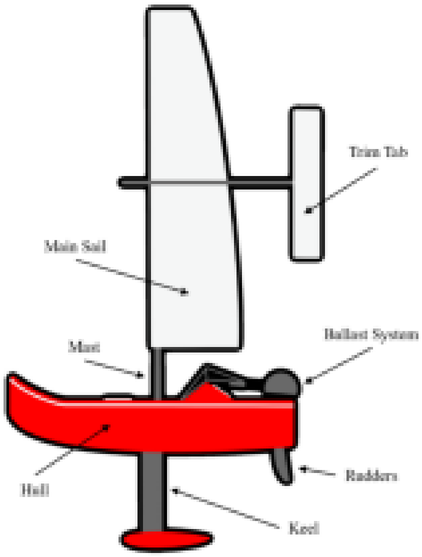


Figure 2: Anatomy of Sailbot 20-21

only have one rudder, however, Sailbot has two rudders controlled by a single servo motor. Sailbot’s rudders are designed such that one will be vertical when the boat is heeled to the desired angle of 20 degrees.

The next system is the sail assembly. The mast is a vertical pole used to support the sails. In traditional boats, the mast is held upright and supported using wires called shrouds (or stays). Attached to the mast is the sail, which is extended using the boom, a horizontal pole that attaches to the mast. The position of the sail is controlled by the mainsheet, see Figure 1. Sailbot utilizes a rigid sail assembly instead of a traditional cloth sail. The rigid sail assembly consists of three main components: the mast, the mainsail, and a trim tab (Figure 2). Unlike the mast of a traditional sailboat, the mast for a rigid sail is freely rotating and does not have stays or additional supports. Additionally, the position of Sailbot’s rigid sail is controlled using a trim tab instead of a mainsheet.

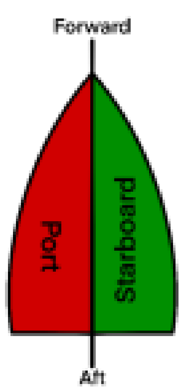


Figure 3: Diagram of port and starboard sides of a boat

The comprehension of the proper terminology of location and direction in a boat is critical in addition to understanding each part/system and its function within a sailboat, see Figure 3. The bow

of the boat is the front of the vessel, and the stern is the back. To explain relative positions in a boat, the terms forward and aft are used, instead of in front of or behind, respectively. Forward refers to anything near the bow within the reference frame of the boat, and aft refers to anything near the stern. While in open water, using the terms right and left can be arbitrary, and therefore are not detailed descriptors of position. Instead, the terms starboard and port are used to describe the position. Starboard refers to the right-hand side of the boat (when facing the bow), and port refers to the left-hand side.

2.1.2 Points of Sail

To successfully operate a sailboat, the position of the boat relative to the direction of the wind and the corresponding optimal sail trim must be understood. These relations are summarized by the six points of sail. The first point of sail is the no-go zone also referred to as being in irons or the no-sail zone (Figure 4). The no-go zone is too close to the wind to sail effectively because the sail cannot generate enough lift in the desired direction. To sail to a point that is directly into the wind, a method of zigzagging across the no-go zone must be utilized. Sailing towards the direction in which the wind is blowing is referred to as upwind sailing. Upwind sailing includes two points of sail: Close Hauled and Close Reach (Figure 4). While sailing on these two points of sail the sails are trimmed in close to generate maximum lift. The next point of sail is a Beam Reach, this refers to the position when sailing across the wind (Figure 4). In this position the sails are trimmed “half in half-out". The final two points of sail are used when sailing away from the wind, referred to as downwind sailing. Downwind sailing is in the direction in which the wind is blowing. The two points of sail included in downwind sailing are Broad Reach and Running (Figure 4). The sails are trimmed most or all the way out when on these points of sail.

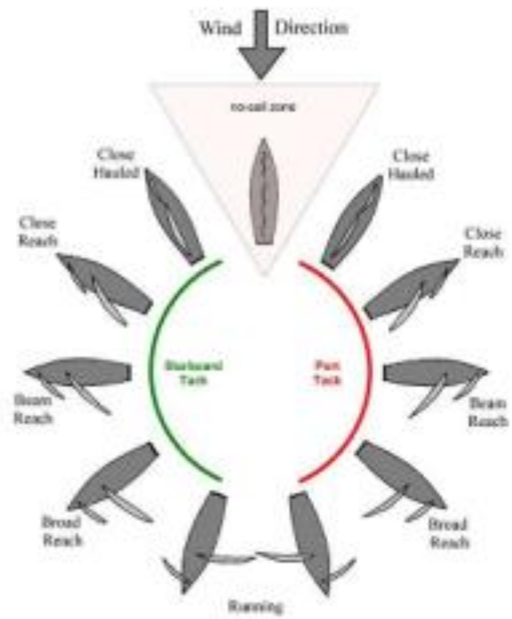


Figure 4: Points of sail

2.1 Sailing Basics 5

The points of sail are symmetrical across the wind, regardless of what side of the boat the wind is coming across. The side of the boat over which the wind is coming from is referred to as a tack. A port tack is when the wind is coming over the port (left) side of the boat, and a starboard tack is when the wind is coming over the starboard (right) side of the boat. The port tack is shown with a red semi-circle in Figure 4 and the starboard tack is shown with a green semi-circle in Figure 4.

The final concept to understand is windward versus leeward. Windward means upwind, or the direction from which the wind is blowing. A windward vessel refers to the vessel that is upwind of the other vessel, the leeward vessel. Leeward refers to downwind, or the direction opposite to the way that the wind is blowing from.

2.1.3 Tacking and Jibing

There are two basic turning maneuvers when operating sailboats: tacking and jibing. Understanding the difference between the two techniques requires an understanding of the wind direction and the points of sail stated above in section 2.1.2. Both tacking and jibing are used to change the tack of the boat, the side of the boat that the wind is coming over, which consequently switches the side of the boat the sail is on. Tacking refers to the maneuver in which the bow of the boat turns through the wind. Tacking is mainly used when sailing upwind while close-hauled or on a close reach. Jibing refers to the maneuver in which the stern of the boat passes through the wind. A jibe is used to maneuver the boat when sailing downwind, either on a broad reach or while on a run.

A tack is demonstrated in Figure 5a, in which the boat changes from a port tack (red) to a starboard tack (green) while sailing upwind. The boat is initially sailing on a port tack close-hauled (red), then the bow passes through the wind (white), and the boat continues sailing on a close hauled starboard tack (green). A jibe is demonstrated in Figure 5b, in which the boat changes from

a port tack (red) to a starboard tack downwind (green). The boat is initially sailing on a port tack on a broad reach (red), then the stern of the boat passes through the wind (white), and the boat continues sailing on a broad reach starboard tack (green).

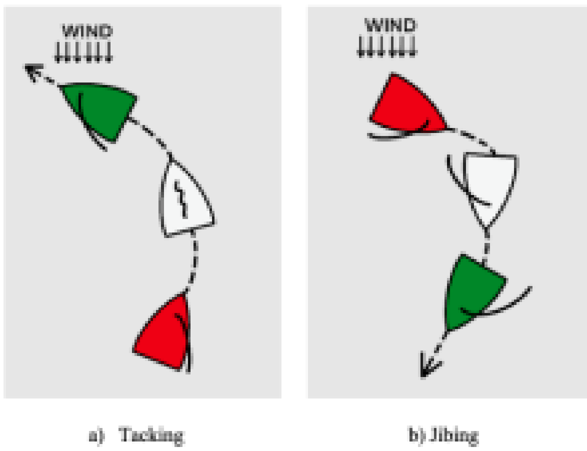


Figure 5: Tacking vs jibing

2.1 Sailing Basics 6

2.1.4 Rights of Way

While operating any vessel it is imperative to understand the boating right of way rules, comparable to “rules of the road” on land. Right-of-way rules are specifically designed maneuvering regulations for the purpose of avoiding collisions between vessels. The five main right of way rules are as follows (*Understanding Boating “Right of Way” Rules*, 2021):

1. Vessels under sail have the right of way over powerboats (with some exceptions).

2. When crossing, the boat on the right (approaching from starboard) has the right of way.

3. When meeting head-on, each vessel must alter course to starboard.

4. Any vessel overtaking another must keep clear of the stand-on vessel.

5. When approaching another vessel whose intentions aren’t clear, take evasive actions early.

The five rules stated above must be understood by all vessels. In addition to the general boating right of way rules, there are specific right of way rules that sailboats must also adhere to. During the IRSR vessels will be exposed to situations in which two sailboats meet, in which the following rules will apply (*Understanding Boating “Right of Way” Rules*, 2021):

1. The boat on the starboard tack (wind coming over the starboard side) has the right of way.

2. When two vessels are on the same tack (wind is coming from the same side), the leeward (downwind) boat has the right of way over the windward (upwind) boat.

3. When on the same tack in a passing situation, the vessel being overtaken has the right of way always.

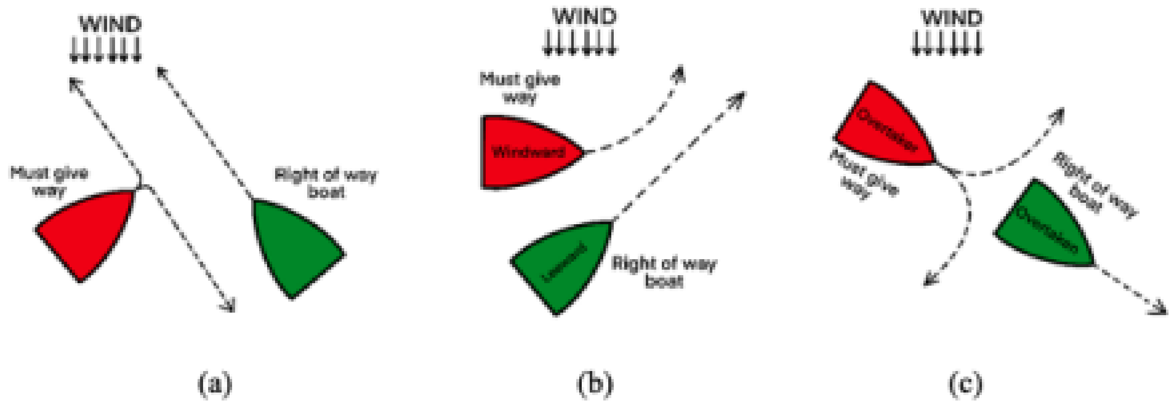


Figure 6: Examples of right of way scenarios

Figure 6a demonstrates sailing rights of way rule 1, in which the starboard tack boat (green) has right of way over the port tack boat (red) which must give way by heading off or tacking to avoid.

2.2 Sailing a Robotic Sailboat with a Rigid Wingsail 7

Figure 6b demonstrates sailing rights of way rule 2, in which two boats are on the same tack and the leeward boat (green) has the right of way over the windward boat (red). Therefore, the windward boat must head up or tack to avoid the leeward boat. Figure 6c demonstrates sailing rights of way rule 3, in which two boats are on the same tack and in a passing situation. The overtaking boat (red) must give way to the boat that is being overtaken (green) by heading up or down.

The comprehension of the eight rules stated above is crucial to maintain safe boating conditions for all vessels, especially during the IRSR.

2.2 Sailing a Robotic Sailboat with a Rigid Wingsail

This section presents the physics of sailing with a rigid wingsail. For most points of sail, our robotic sailboat is propelled through the water predominantly due to the lift generated by the rigid wing sail. The total aerodynamic force on a wingsail has two components – lift, which acts perpendicular to the wind direction, and drag, which acts in the same direction as the wind (Figure 7). Drag tends to push the sail downwind, which is sideways on most points of sail. However, when sailing on a run, drag is the predominant force and it pushes the sailboat forward since the direction of travel is directly downwind. It should be noted that Sailbot's mast is designed to freely rotate, such that when the boat travels at an angle with the apparent wind, the wingsail will tend to rotate until the angle of attack (AoA), the angle between the apparent wind and the chord line, reaches zero degrees.

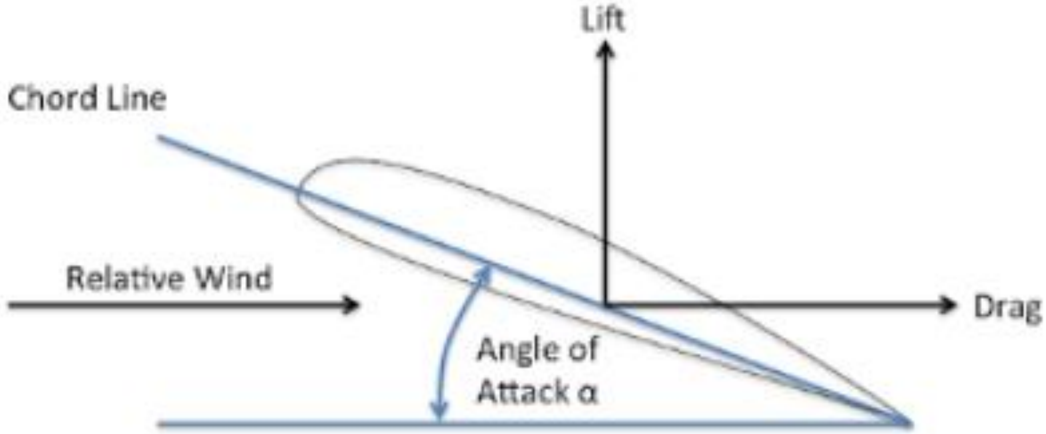


Figure 7: Diagram of angle of attack, lift vector, and drag vector on an airfoil

Sailbot's wingsail is fitted with a trim tab, a smaller secondary symmetrical foil that is mounted midway up the mast at the end of two long booms that extends beyond the sail. This airfoil, like the airfoils in the wingsail, is also subject to lift and drag forces based on its angle of attack with the apparent wind. Its purpose is to help the sail maintain its desired AoA. The trim tab does this by creating a counteracting moment opposing the moment created by the wind on the wingsail when the wingsail develops any AoA. A static equilibrium between these moments balances out the wingsail, keeping it at the intended AoA.

8.2 | Appendix B: Rigid Sailing and Trim Tab Information (Stafford, 2021)

Lift in a wing (or sail) is defined as the force vector perpendicular to the free stream fluid velocity (henceforth called "apparent wind direction or AWD"). A symmetric airfoil (or, indeed, hydrofoil) develops lift anytime there is an angle between the AWD and the line from leading edge to trailing edge of the wing (the "chord line"). This is called the "angle of attack or AoA". On a sailboat it should be clear that as long as the AWD has a non-zero angle with the intended direction of travel (this angle is called the "sailing angle or SA"), the lift vector can be broken into a component that would tend to drive the sailboat forward and an orthogonal component that would tend to drive the sailboat in the leeward/sideways direction. Practically speaking, the minimum SA on a well-designed sailbot where the forward force component is sufficient to make forward progress will be about 30-40 degrees.

1. When on a starboard tack, the trimtab will have an offset in a CW direction from its boom centerline (Port tack: CCW; i.e. the trimtab should always point to windward relative to its boom).

2. Providing the critical hull heel angle is not exceeded (~40 degrees) and the boat is commanded to move in a direction not downwind, the Teensy should always be controlling the trim tab to attain the max L/D AoA as measured by the wingsail's AoA sensor.

3. When going downwind, Teensy should set the trim tab for max excursion (port or starboard).

4. When heel angle exceeds preset max, Teensy needs to command trimtab so as to reduce the wingsail's AoA.

5. The Teensy needs the following inputs:

a. Wingsail AoA from wingsail sensor (to adjust servo)

b. Angle of heel from AirMar sensor (to enter feathering/reduced heel realm)

c. Commands from hull:

i. Zero lift (to stop and the failsafe condition)

ii. Starboard Max L/D (to go upwind or reach with wind coming across starboard side of boat)

iii. Port Max L/D (ditto for wind on port side)

iv. Starboard Max Drag (to go straight downwind from starboard reach)

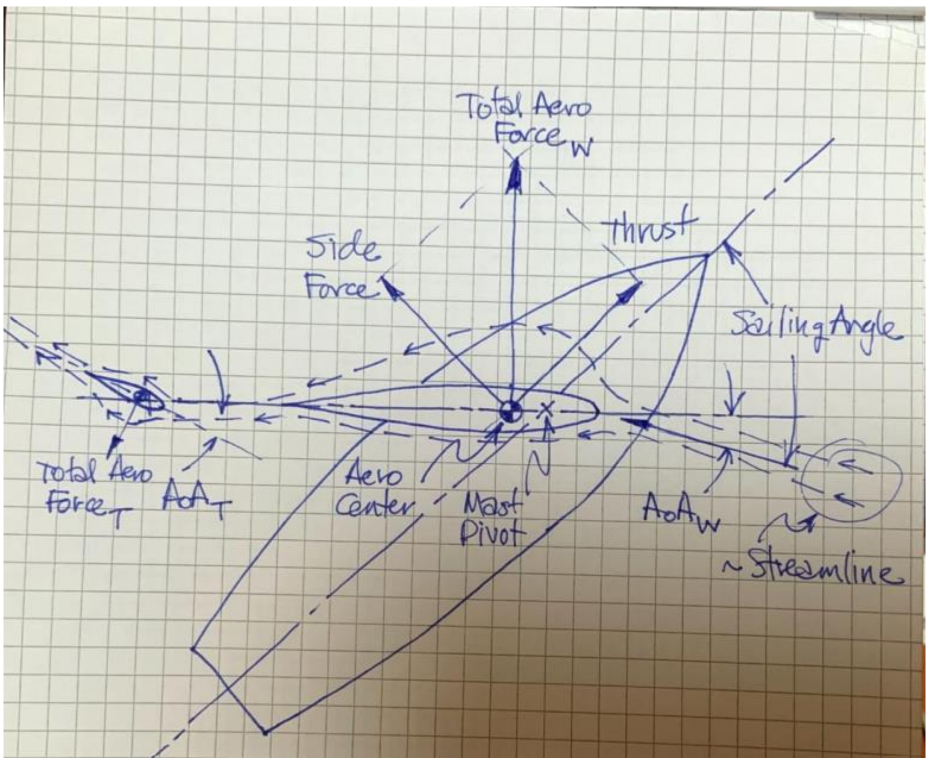
v. Port Max Drag (ditto from port reach)

A few other considerations are worth noting.

1. First is that the AWD (measured by the AirMar) is only equal to the true wind direction when sailbot is not moving. Once underway, the true wind direction and velocity are only available through calculation (by the AirMar) by doing the vector math with the actual hull track angle and speed.
2. The SA will normally be close but not exactly the angle between boat heading and AWD. To produce forces to counteract the leeward wingsail force component, the underwater "wingsail", i.e. the keel, needs a positive AoA (it is also a symmetrical foil). When going hard to windward, the keel's AoA can be up to 15 degrees (much larger if you get too slow or attempt to sail too close to the wind direction). This means that sailbot's track will vary from its heading by the keel's AoA.

3. The “tell-tales” on the wingsail are the best way to see if it is at the max L/D AoA. When set appropriately, both windward and leeward ribbons should be streaming aft with the leeward ones occasionally starting to lift off the wing surface. When the leeward ones are streaming downward or in the reverse direction it means the wingsail’s AoA is too large and the wingsail is “stalled” (high drag/minimum lift).

4. There are actually 5 separate symmetrical foils on sailbot, all subject to AoA, lift/drag, and stall considerations. These are of course the wingsail, the trimtab, the keel, and the rudders.

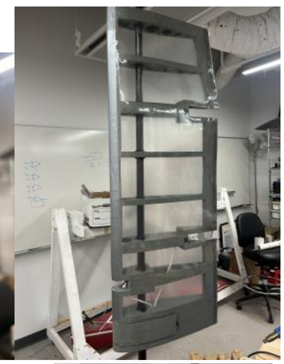


8.3 | Appendix C: Photos of the Sail Construction Process

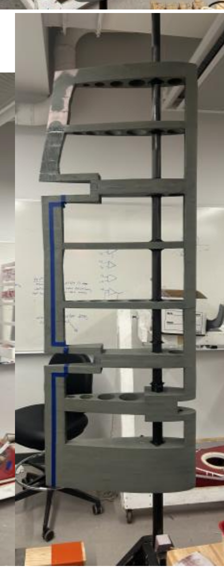






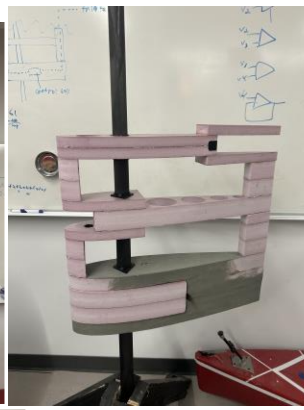



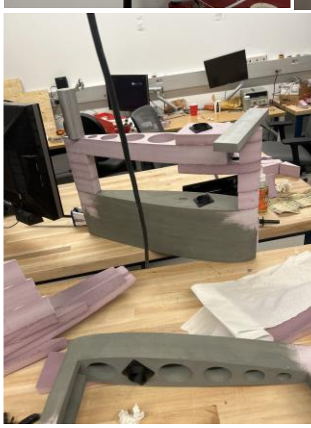


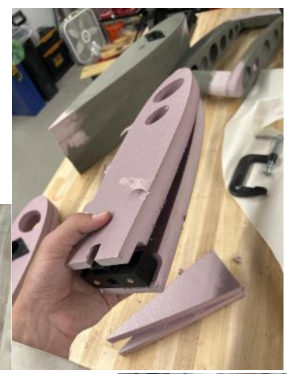



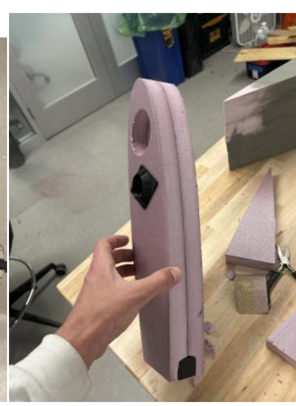




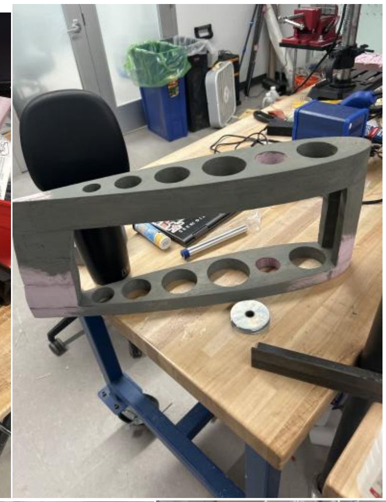



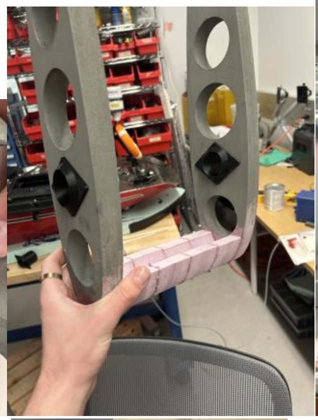
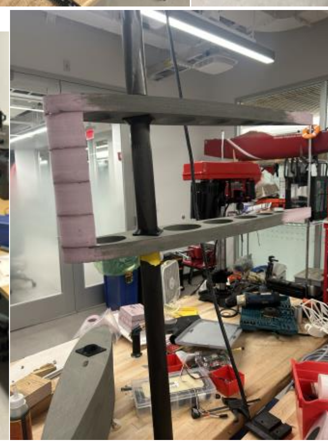



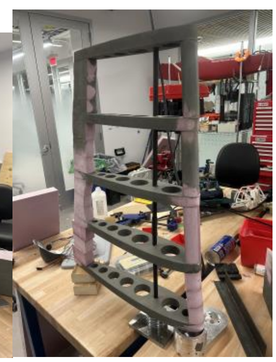




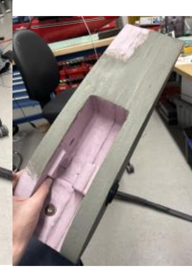



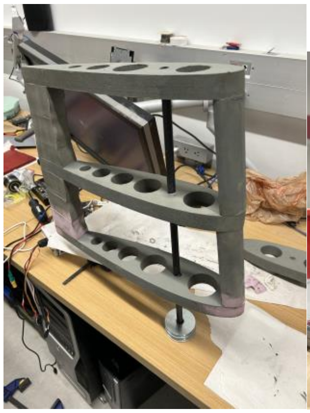







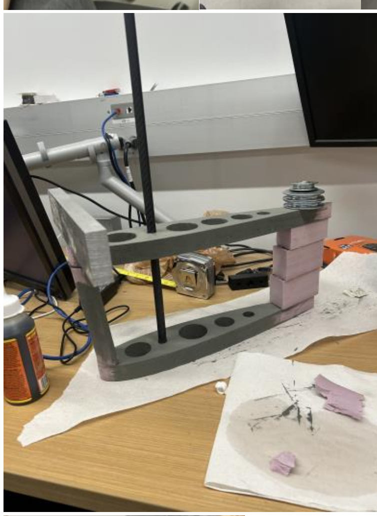


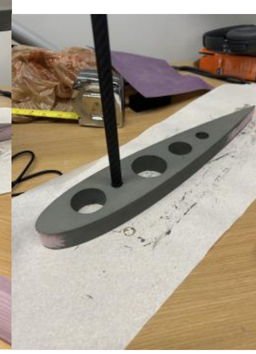
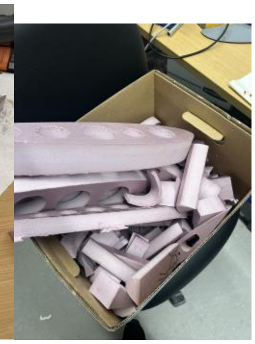












8.4 | Appendix D: Supplemental Data

File: Old_vs_New_Rudder_Performance_Data.xlsx

Description: Contains lift and drag simulation results for old and new rudder geometries at 0°, 5°, 10°, and 15° angles of attack. Data used to generate Figures 21–23.