The Robotic Automated Wingsail:

The development of a rigid wingsail for a 2-meter model sailing vessel.

A Major Qualifying Project Report
Submitted to the Faculty of

In partial fulfillment of the requirements for the
Degree in Bachelor of Science
By

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Date:_______________

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Professor Kenneth Stafford

Acknowledgements

We would like to thank our advisor, Professor Stafford for his advice throughout this project, as well as the SailBot team whom we worked closely with. We offer our regards to Nicholas Gigliotti who aided us in manufacturing and during the collaboration portion of this MQP. Finally, we would like to thank the many professors who offered their wisdom during the course of this MQP: Professor Michalson, Professor Linn, and Professor Olinger. We wish the SailBot team best of luck in the 2017 SailBot competition and all future endeavors.

Abstract

This project sought to create an autonomous sail for use on a 6.6ft hull to be entered in the two meter class of the 2017 SailBot competition. An innovative alternative to the standard cloth sail was sought to allow for greater lift forces than that of a standard sail. To solve this problem, a robotic automated wingsail was developed based on the existing design of the Greenbird sail-car. The wingsail is composed of two wings, the main sail and the trim tab. The trim tab alters the angle of attack of the main sail to produce maximum or minimum lift or drag. The final wingsail design is adaptable to various sailing vessels, allowing it to serve a purpose beyond the SailBot competition.

Executive Summary

Each year the SailBot competition, an international robotic sailing competition, hosts schools from around the world to compete in a series of sailing related challenges. The event consists of six different objectives of which the vessel is to attempt. These six objectives include: the fleet race, station keeping, navigation, presentation (ingenuity), a long distance race, and collision avoidance test. For these challenges there are different levels of human interaction that are allowed; for example, in the fleet race there can be remote control by a human operator, station keeping incurs a penalty if there is remote control, and the collision avoidance test is to be completely autonomous. Teams can enter in one or two meter categories. The 2017 competition is to be held from June 11th to the 16th at the United States Naval Academy. For the 2017 competition, the WPI SailBot team will enter a vessel into the two meter category. The goal of the team is to enter as many tests within the competition as possible to secure a victory.

This MQP involved the construction of one component of the vessel to be entered: the sail. In years past, a traditional Mylar sail has been utilized. Our team, the Robotic Automated Wingsail, looked for an innovative solution to the traditional sail that would be able to generate higher levels of lift forces, as well as increase points scored in the presentation category. Our final conclusion was to use a self-trimming wingsail such as that used on the Greenbird car. Our project was broken down into three terms consisting of design, prototyping, final construction, and testing. Working in conjunction with this MQP was the SailBot MQP whose primary work involved the hull and navigation systems. For successful integration of the two MQPs, close collaboration was necessary.

To begin the project, emphasis was placed on completing initial design and analysis on key system components including the airfoil shape, necessary robotic inputs, and mast selection. Constraints such as weights and maximum forces placed on the hull were discussed with the SailBot MQP. Once the initial airfoil design was selected, a 15% and ½ scale model were constructed by the team. The primary focus of the 15% scale model was to determine the aerodynamic nature of the wingsail; specifically testing the stall capabilities of the trim tab. The ½ scale model focused heavily on construction techniques that would later be used in the full scale model. Primary conclusions from the scale models where that the trim tab does have enough authority to fully stall the main sail, polycarbonate was not an effective leading and trailing edge, and practice was needed in applying Monokote as the covering of the wingsail. Following, the team moved towards the construction of the full scale model that included the revised design specifications.

The full scale model consists of a Naish RDM windsurfing mast, sanded plywood airfoils, a balsa and fiberglass leading edge, carbon fiber trailing edge, and Monokote covering. The wingsail is wholly autonomous and includes a servo driven trim tab. Further collaboration was needed with the SailBot MQP team to constrain the wingsail within the hull. We acquired a shaft collar and designed the upper bearing, while the other MQP team designed the lower bearing system. The final wingsail sits roughly 11’ tall. Testing for the lift and drag, actuation of the system, and transportation were completed to determine the success of the system.

Authorship

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Executive Summary	Kelsey Regan	Danny Singer
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Background	Dean Schifilliti	Danny Singer
Schedule	Kelsey Regan	Danny Singer
Collaboration	Dean Schifilliti	Danny Singer
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Analysis and Preliminary Design	Kelsey Regan	Danny Singer
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Determining Wingsail Dimensions with Excel	Danny Singer	Kelsey Regan
Mast	Kelsey Regan	Dean Schifilliti
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Bearings/Bushings	Danny Singer	Kelsey Regan
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½ Scale Model	N/A	N/A
Robotic Implementation	Dean Schifilliti	Danny Singer
Mast	Danny Singer	Kelsey Regan
Connecting Rods	Danny Singer	Dean Schifilliti
Leading Edge	Kelsey Regan	Danny Singer
Trailing Edge	Kelsey Regan	Danny Singer
Coating	Kelsey Regan	Danny Singer
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1/2 Scale Model	Danny Singer	Kelsey Regan
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Robotic Development	Dean Schifilliti	Danny Singer
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Skeleton	Danny Singer	Kelsey Regan
Trim Tab Actuation System	Dean Schifilliti	Kelsey Regan
Mast	Kelsey Regan	Danny Singer
Leading Edge	Kelsey Regan	Danny Singer
Trailing Edge	Kelsey Regan	Danny Singer

Coating	Kelsey Regan	Danny Singer
Counterweight System	Danny Singer	Kelsey Regan
Drainage System	Kelsey Regan	Danny Singer
Main Joint	Danny Singer	Kelsey Regan
Validation and Analysis of Full Scale Wingsail	Kelsey Regan	Danny Singer
Lift and Drag Test	Danny Singer	Kelsey Regan
Torque Test	Danny Singer	Kelsey Regan
Weighing Wingsail Components	Kelsey Regan	Danny Singer
Transportation	Kelsey Regan	Danny Singer
Social Implications	Dean Schifilliti	Kelsey Regan
Recommendations and Conclusions	Danny Singer, Dean Schifilliti, Kelsey Regan	Dean Schifilliti

Table 1: Authorship Table

Table of Contents

Table of Figures

Table of Tables

Table of Equations

Useful Terminology

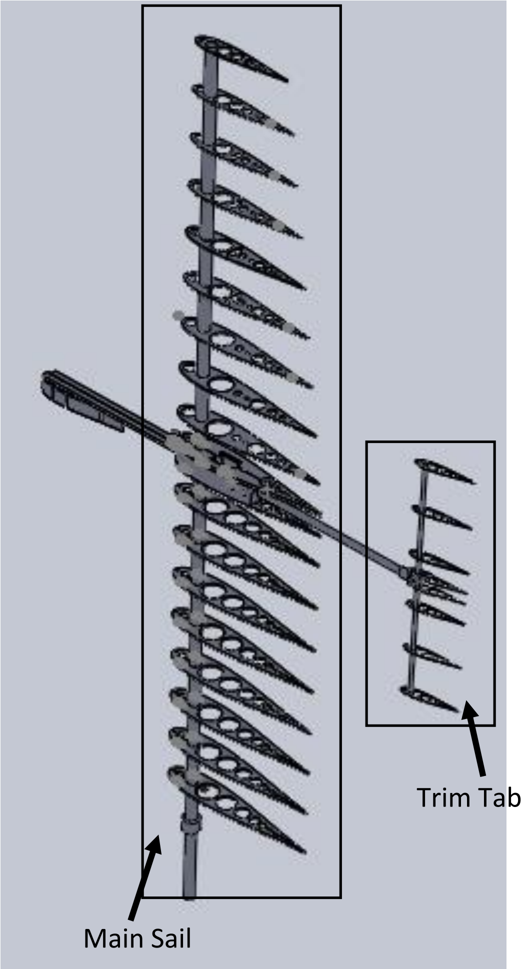


Figure 4: Main Sail & Trim Tab

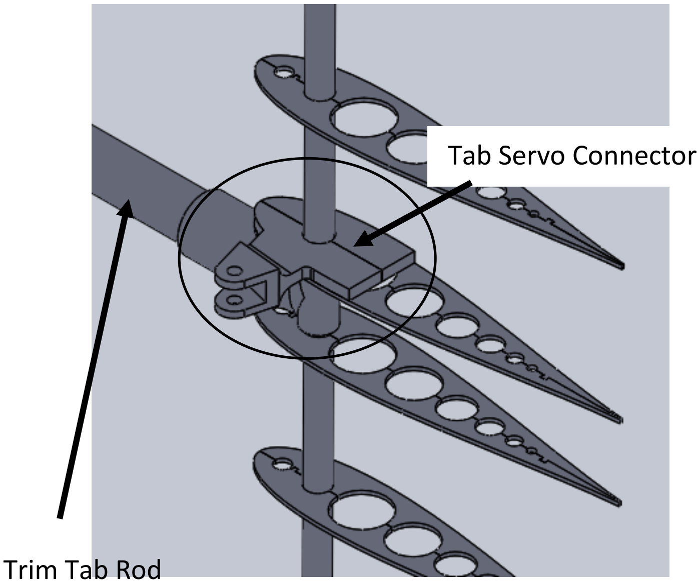


Figure 3: Tab Servo Connector

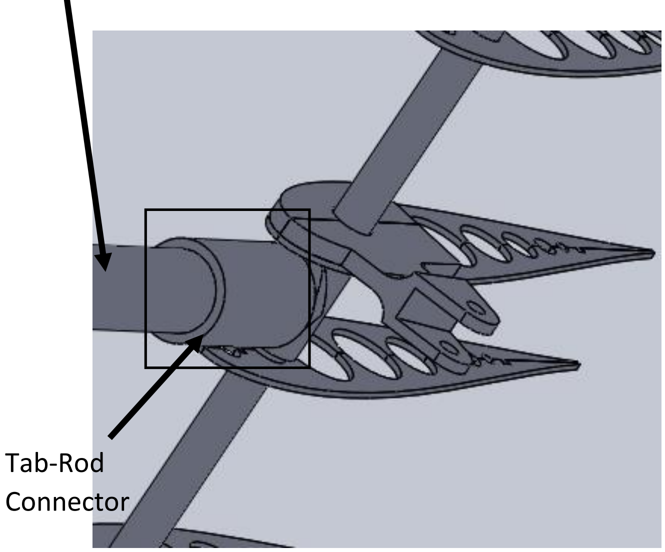


Figure 2: Trim Tab Rod & Rod Connector

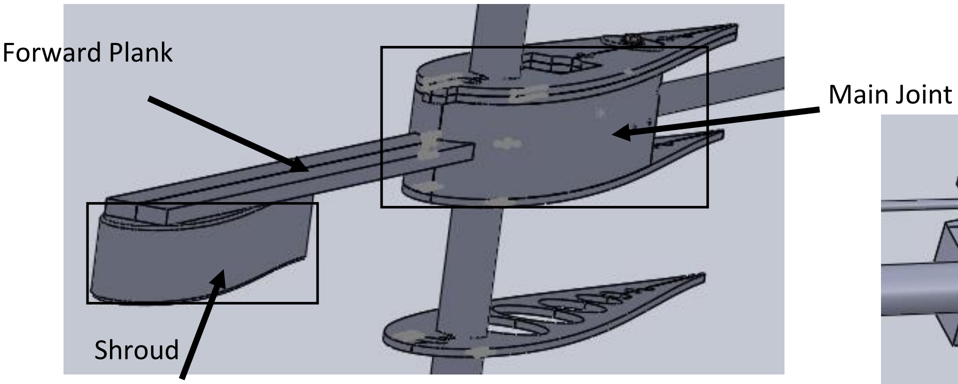


Figure 1: Counterweight

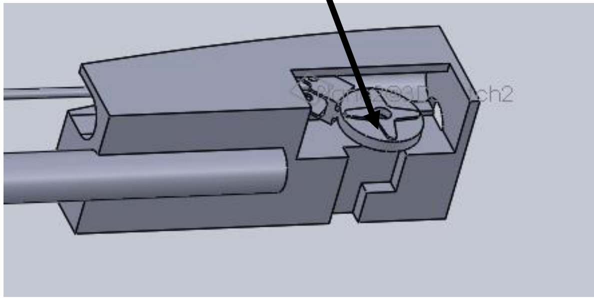


Figure 5: Servo

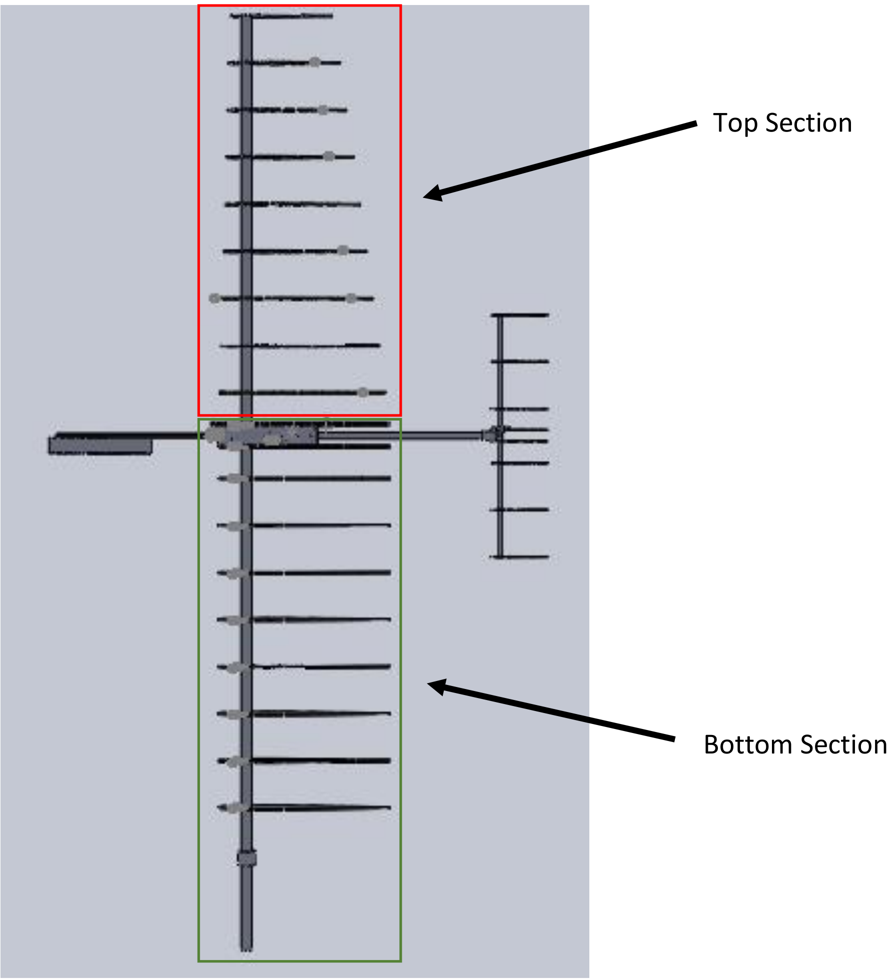


Figure 6: Sections of Sail

Heeling – Inclination along the longitudinal roll axis caused by the moments created by aerodynamic (i.e. from the wingsail) and hydrodynamic (i.e. from the keel) forces.

Introduction

SailBot is an international robotic sailing regatta which hosts one meter and two meter classes. The event consists of six different objectives of which the vessel is to attempt. These six objectives include: the fleet race, station keeping, navigation, presentation (ingenuity), a long distance race, and collision avoidance test. For these challenges there are different levels of human interaction that are allowed; for example, in the fleet race there can be remote control by a human operator, station keeping incurs a penalty if there is remote control, and the collision avoidance test is to be completely autonomous. The 2017 SailBot course map can be seen below in Figure 7. The main course area pictured in the figure is $2.69*10^{4}$ square feet ($9.65*10^{-4}$ square miles), with the long distance race set on a course of length one nautical mile, or 1.15 statute miles (Sailbot.org).

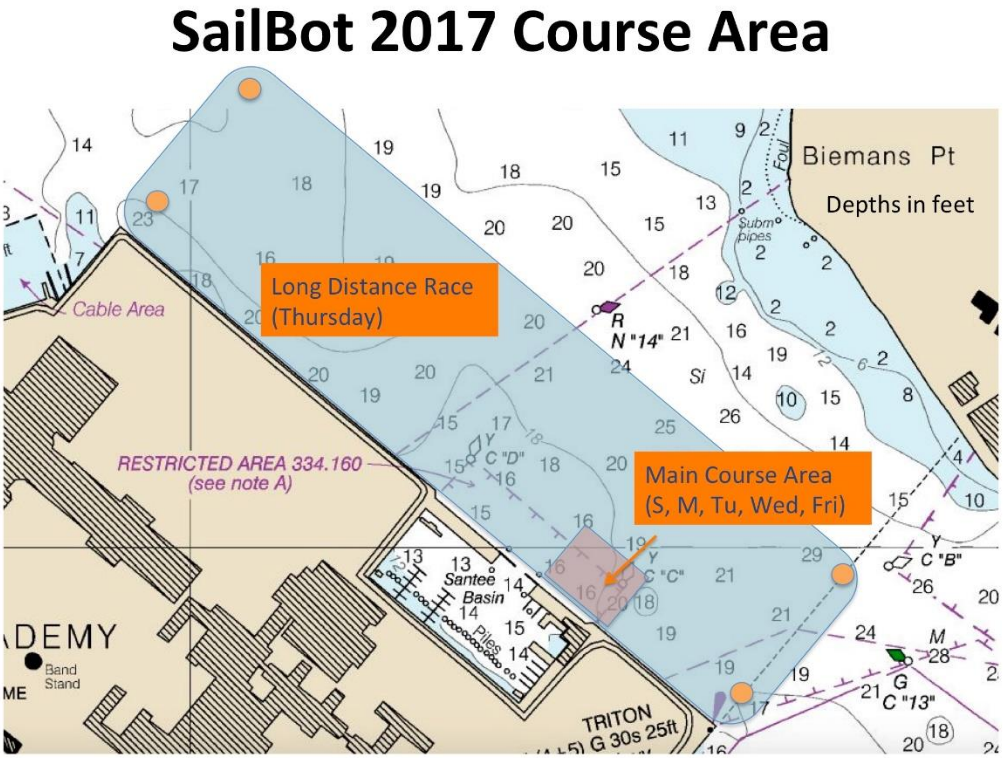


Figure 7: 2017 SailBot Course Map
http://sailbot.org/

One of the primary categories of interest is the navigation portion of the competition. The navigation portion is wholly autonomous, meaning there is no manual control allowed once the vessel enters the race course. The wingsail must allow the boat to sail between and around buoys that designate the path. The image seen below is a view of the course that will be sailed in the navigation competition. The course is held within the main course area pictured in Figure 7, and consists of approximately 164' of upwind sailing (sailbot.org). Many of the design specifications for the MQP were driven by the navigation portion of the competition and its successful completion.

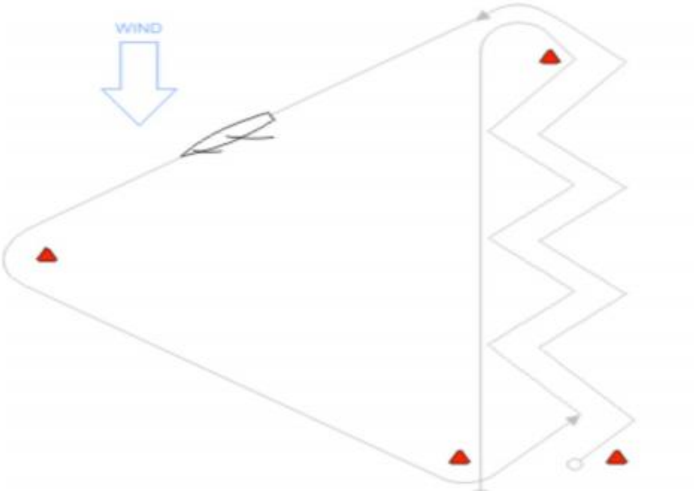


Figure 8: Navigation Course

Inspiration for this MQP was driven by the Greenbird sail-car, the "fastest wind powered vehicle on Earth" (Greenbird).The car is driven by a self-trimming wingsail and is able to reach speeds of 126.2mph. The project is led by engineer Richard Jenkins and Ecotricity, who is the largest green energy electricity company in the U.K. (Greenbird).

Figure 9: Greenbird Sail-car

Background

Last year's WPI SailBot team used a traditional soft Mylar sail, with the goal of this project being to introduce a rigid wingsail system to complete the previously mentioned challenges and increase the points scored in the presentation category.

There are multiple categories of sails that were considered for this project. To determine which would be implemented, a decision matrix comparing a self-trimming rigid wingsail, a segmented adjustable camber rigid wingsail, and a more traditional cloth sail for comparison to last year's bot was utilized.

Multiplier	Category	Self-trimming	Segmented	Cloth
4	Speed(upwind)	6	8	5
2	Speed(downwind)	3	7	5
4	Manufacturability	8	6	9
3	Control Complexity	8	5	3
3	Robustness & Durability	8	3	7
4	Dead Zone Size	5	7	6
3	Ease of Mounting	5	4	6
	Total	145	134	138

Table 2: Decision Matrix

Terms used in the matrix are defined below-

- Manufacturability- The ability to produce components of the sail, and the ability to repair and produce new replacement components on campus.
- Durability- The ability to withstand wakes, wind, corrosion, and the number of components that are heavily susceptible to wear (ex.motors) etc.
- Dead zone- The area in which no lift is generated- with the intent to minimize this zone.
- Ease of controllability- The number of motors, servos, links, joints, etc, to control wingsail.

Our reasoning behind the scoring of each sail type in the provided categories is presented below in Table 3.

Categories	Self-trimming	Segmented	Cloth
Speed(upwind)	.7-1.25 lift coefficient	2-2.5 lift coefficient	1.5-2 lift coefficient
Speed(downwind)	Symmetrical wingsail camber cannot be adjusted.	Adjustable camber allows for optimization of airfoil shape for conditions.	Cloth sails are not as efficient as wings, but the camber can be adjusted.
Manufacturability	Single airfoil, single mast, airfoil can be produced in large quantity.	Tab can be removed for transportation; multi-airfoil design, addition of hinge joint or second mast.	If sail rips, it either has to be patched or replaced. Winches, pulleys, spooling, etc.
Control Complexity	Requires 1 small motor, easy to maintain, easy to fix, tailpiece, as non-experienced sailors we wanted to be able to utilize the wingsail.	Much harder to transport, requires multiple, more powerful motors.	Requires experienced sailing crew.
Robustness and Durability	Motor is above waterline, less chance of getting wet.	Easier to replace and stock replacement parts for one sail as opposed to two different ones; more parts and motors that can break wires can break, tension lost, harder to fix quickly.	Fine motor adjustments required e.g., knots, maintaining proper tension, etc.
Dead Zone Size	Larger dead zone than segmented.	Smaller than cloth sail.	Smallest dead zone.
Ease of Mounting	Tab can be detachable for easier transportation, mast must be driven down into the hull of the boat.	Can use worm drive, transportation can be difficult as sail is larger and has multiple components that can break.	Can be mounted on the top of the hull.

Table 3: Decision Matrix Reasoning

Based on our research the most advantageous sail was the self-trimming wingsail. The self-trimming wingsail operates with a free spinning main sail that acts as a wind vane unless acted upon by the actuation of the trim tab. Mounted off of the back of the sail is a much smaller sail referred to as a trim tab. This trim tab is controlled by a servo and is used to change the angle of attack of the main sail.

Schedule

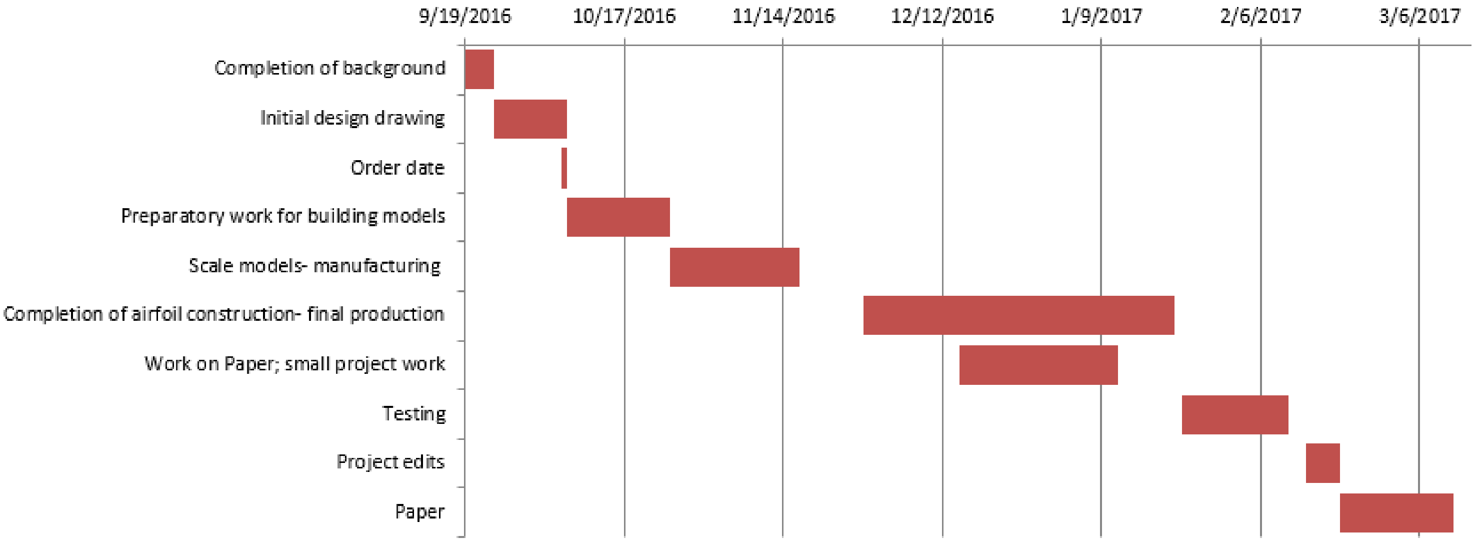


Figure 10: Gantt Chart

Important Dates	
Preliminary Design Review	11/22/2016
Critical Design Review	2/16/2017
Project Completion	3/24/2017

Table 4: Important Dates

Above in Table 4 and Figure 10 are our self-designated work schedule and deadlines. The Gantt chart was designed starting with the culmination of the project and testing at the end of the three term schedule. The first term of the project began with the initial design of the wingsail, followed by the ordering of the necessary parts at the end of the term to use the week of break as shipping time. The second term of the project consisted of the construction of a model to ensure our designs provided adequate results before we began the full size manufacturing. The final term of the project was divided into construction of the custom testing equipment, testing, and final report completions.

Collaboration

Our project worked closely with another MQP team, SailBot, whose project was to design the hull, navigation, and electrical systems. It was crucial that our teams remain involved in each other's projects due to the large interaction between our products. During the design phase for our full scale model we continuously exchanged and worked cooperatively on CAD files to ensure that the geometries were compliant. This continued throughout the project’s life. The SailBot team assisted us in the fiberglassing process. The SailBot team had experience from fiberglassing their hull and offered their experience to us going forward with our fiberglassing of the main sail and trim tab. Collaboration was also necessary for design of the tube which the main sail is mounted in and the method for free rotation of the main sail. General guidelines such as total height and length were exchanged between the two teams to ensure the rules of the competition were met. We worked closely with the SailBot team in regards to communication and control as well. As the project developed there were changes that continued to form, however there was cooperative assistance with the changing communications designs and functionality as the project progressed. For a detailed description of all collaboration, see the collaboration document in Appendix F.

Design Requirements and Specifications

The points located in Table 5 are those by which we based our success of the competition requirements on. The wingsail was also judged on properties not required by the SailBot competition. The bullets listed in Table 6 demonstrate the requirements set by the Robotic Automated Wingsail team and Professor Stafford that fall within this category. These requirements have been sub-categorized into requirements for the mechanical engineering and robotics engineering teammates.

SailBot Based Requirements

Project Objectives- ***Required for SailBot*** Competition			
Goal Number	Goal	Success or Failure	Evidence of Success or Failure
1	The wingsail must be able to travel in both upwind and downwind conditions. Meaning when traveling upwind, the wingsail must present tacking capabilities.	Upon Completion	Upon Completion
2	The wingsail must present a method to stop generating a thrust force on the wingsail.	Upon Completion	Upon Completion
3	Overall length including hull, all spars and foils oriented in their fore and aft directions and at their maximum extensions if applicable, shall not exceed two meters measured parallel to the waterline.	Upon Completion	Upon Completion
4	Beam shall not exceed three meters overall width at zero heel angle.	Upon Completion	Upon completion
5	Total overall height from the lowest underwater point to the highest point on the largest rig shall not exceed five meters. (Sensors and mounting not included).	Upon Completion	Upon Completion

Table 5: Project Objectives- Required for SailBot Competition

Logistical and Practical Requirements

Project Objectives- ***Non-SailBot*** Requirements			
Goal Number	Goal	Success or Failure	Evidence of Success or Failure
6	The wingsail must be capable of being broken up into sections that allow it to be easily transported and to accommodate for various wind velocities.	Upon Completion	Upon Completion
7	Wingsail sections must be able to be re-assembled with tools available to the SailBot team and with relative speed.	Upon Completion	Upon Completion
8	The wingsail must present some method of draining in cases where capsizing occurs.	Upon Completion	Upon Completion
9	Wingsail components must be able to be reproduced at the WPI campus, or parts not self-made must be available through an alternative source.	Upon Completion	Upon Completion
10	The wingsail must be constructed in a manner that allows for easy alteration and attachment to another hull.	Upon Completion	Upon Completion
11	The wingsail and all components related to the wingsail must be constrained to a maximum total weight of 20lbs.	Upon Completion	Upon Completion
12	The wingsail must be able to send and receive messages to the hull's processor.	Upon Completion	Upon Completion
13	The wingsail must be able to sense angle of attack and process this data along with heel angle and desired state to consistently maintain optimal forces.	Upon Completion	Upon Completion

Table 6: Project Objectives- Non-SailBot Requirements

Analysis and Preliminary Design

The following section reviews the initial analysis we completed after selecting the self-trimming wingsail. Initial analysis and design are subcategorized into robotic and mechanical sections. Robotic analysis consists of the actuation and power transmission, hardware and communications, and sensing and code design. The mechanical analysis and design section applies fundamental static and fluid analysis to make preliminary design decisions. After, construction of the ½ and 15% scale models used to validate our initial analysis is discussed.

Robotic Analysis and Design

Actuation and Power Transmission Selection

With the self-trimming wingsail design chosen, the sequential step in terms of the robotic components was developing the design behind the actuation. Since the wingsail's mast was free spinning there was no need to control that aspect of the wingsail. The control over the main sail comes from the actuation of the trim tab. The angle of the main sail, or angle of attack, is directly correlated with the angle of the trim tab. The ideal angle of attack for the main sail to produce the most net useful force was calculated to be 8-10˚ from the apparent wind. While the optimal angle of attack for windward legs is 8-10˚, the system must have the authority to full stall the wingsail (30˚+ angle of attack) to maximize drag when doing leeward (downwind) legs. The wingsail was also to be capable of achieving maximum lift conditions. As will be discussed in *Testing and Analysis of Scale Models*, we used the 15% scale model in the wind tunnel to determine the appropriate authority of the main sail to achieve stall with a tab angle of 45˚. Including both directions, to port and starboard, there needed to be a total rotational articulation of a minimum 90˚. The desired actuation is an ideal application for a servo motor.

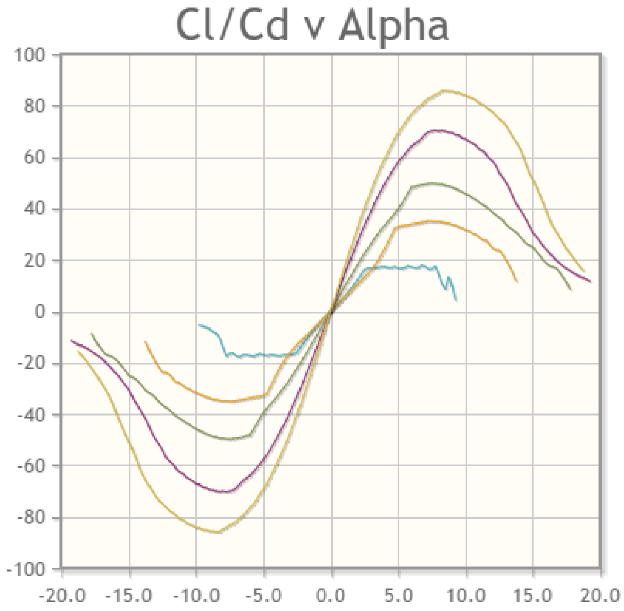


Figure 11: Lift Coefficient over Drag Coefficient versus Angle of Attack per Airfoiltools.com

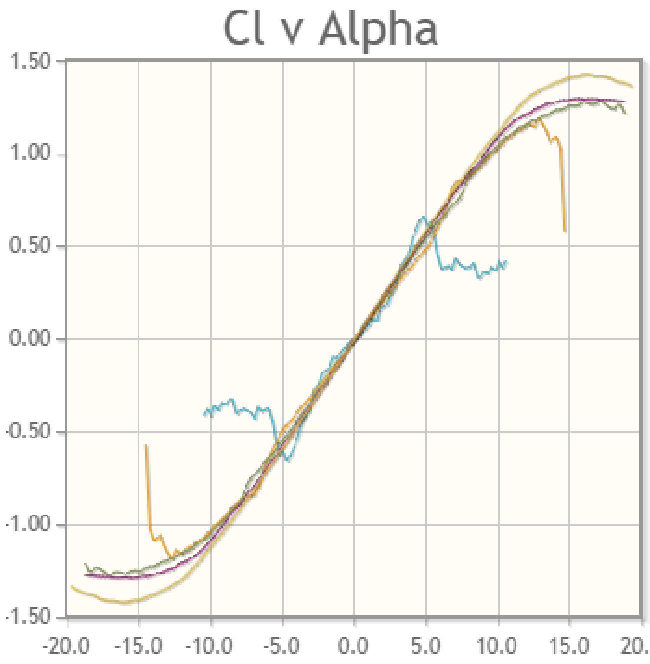


Figure 12: Lift Coefficient vs Angle of Attack of Airfoil Shape per Airfoiltools.com

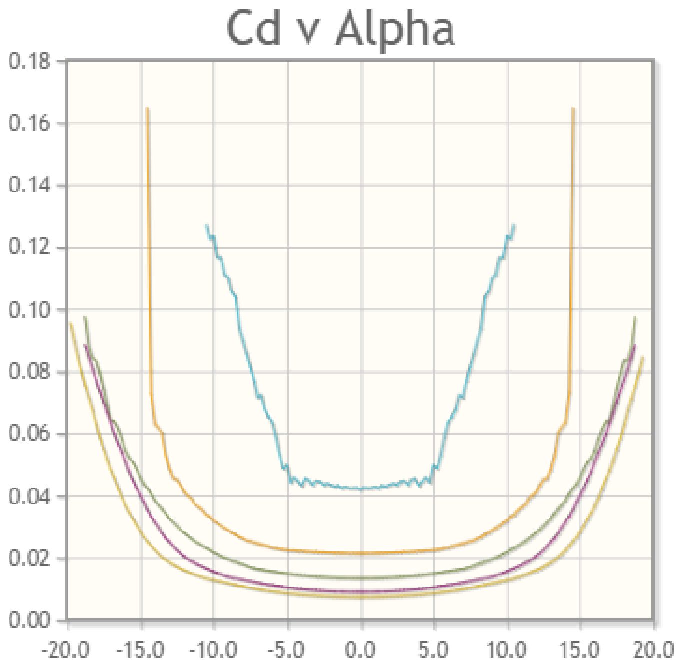


Figure 13: Drag Coefficient vs Angle of Attack of Airfoil Shape per Airfoiltools.com

While the point of actuation is the trim tab rod, mounting the servo in the trim tab itself was deemed unreasonable due to lack of mounting space and added torque on the wingsail under heeling conditions. Ruling out that mounting position and to save weight at a higher position on the main sail, our first idea was to mount the servo on the bottom rib of the main sail and use belts to transfer the torque to the tab. The distance on the full scale over which the torque would have been transferred amounted to

105”, when accounting for both sides of the belt it would have been 210”. Using a belt, especially over this distance, would have required perfectly tensioned, no stretch material to avoid undesired play in the system. By using a micro servo to cut down on weight it was decided that mounting the servo inside the main sail on the same level as the tab would significantly cut down to the transmission distance, while minimally increasing the weight at a higher location. As an alternative to the belt system, a rigid push-pull rod was decided on to further reduce play in the system. These initial assumptions led to the design of the main joint that could house all of the mentioned features.

The servo was selected from only micro servos as to limit weight up high. Additionally, we required the servo be waterproof, while there ideally will not be much water on or around the servo we deemed this important to ensure the operation and longevity of the motor. With these restrictions, we found a servo with enough torque based on our calculations and a factor of safety. The largest torque requirement for the servo is when the wingsail is at maximum lift. The maximum torque that the servo will be experiencing is 0.23ft-lbs; calculations provided below. With all of these requirements, we settled on the Savox SW-0250MG WATERPROOF DIGITAL MICRO SERVO.

$$D_1 = Mast\ to\ 1/4\ chord$$
$$D_2 = Trim\ Tab\ Mast\ to\ Trim\ Tab\ 1/4\ chord$$
$$L_1 = Lift\ from\ Main\ Sail$$
$$L_2 = Lift\ from\ Trim\ Tab$$
$$D_3 = Main\ Mast\ to\ Trim\ Tab\ Mast$$
$$T = Servo\ Torque$$
$$D_4 = Moment\ Arm\ of\ Servo$$
$$D_5 = Distance\ from\ Trim\ Tab\ Mast\ to\ push\ pull\ rod$$
$$F = Force\ along\ push\ pull\ rod$$

$$L_2 = \frac{L_1 * D_1}{D_3}$$
$$F = \frac{L_2 * D_2}{D_5}$$

Equation 1: Torque on the Trim Tab Calculations

Hardware and Communications Design

Collaborating with the SailBot team, the method of communication between the wingsail and hull was designated to be the NMEA2000 communication standard. NMEA2000 is a plug and play system commonly used in marine vessels and uses four wires to send and receive messages. Due to the wingsail being free spinning, if we were to simply run wires from the hull to the wingsail there would have been no way to guarantee that the wires would not get constricted and possibly disconnect, or restrict the free rotation of the main sail. To solve this, our plan was to use a slip ring that would fit around the mast at just above the deck height.

The first plan was to run the wingsail off of an Arduino, looking into the Arduino Uno, or Arduino Micro. To allow the Arduino to work with the NMEA2000 communications, it needed a CAN (controller area network) port and a CAN transceiver. Ultimately, we decided to utilize the Teensy 3.6 development board because of its CAN ports, which would then only require an external CAN transceiver.

Figure 14: Teensy 3.6

Sensing and Code Design

The wingsail had two primary settings, maximum lift, with starboard and port options, and minimum lift. The goal of maximum lift was for the main sail to sustain a specified ideal angle of attack. With the goal of zero lift, this specified angle would be zero degrees.

In many situations the main sail's angle will be directly proportional to the angle of the trim tab; however, varying wind conditions may cause inaccurate angles if we were to rely on this ratio. Using a no feedback open loop would have been unpredictable, therefore we chose a closed loop system that results in more certain movements. Because of the wingsail's free spinning nature, using data from the wind sensor for direction on the hull would have been useless, unless an encoder or full spinning potentiometer was placed on the mast. However, by placing a wind vane direction sensor on the main sail itself, we are able to receive the wind as apparent to the main sail. While the main sail wind vanes under no lift conditions, the wind sensor will align with the main sail. However, when the tab is actuated the main sail maintains an angle to the wind, the wind sensor is able to line up with the wind and therefore return the angle of attack. On the previous SailBot boat, they had created a sensor that perfectly serves our purpose. The sensor is a low friction absolute magnetic encoder with a counter balanced wind vaning top.

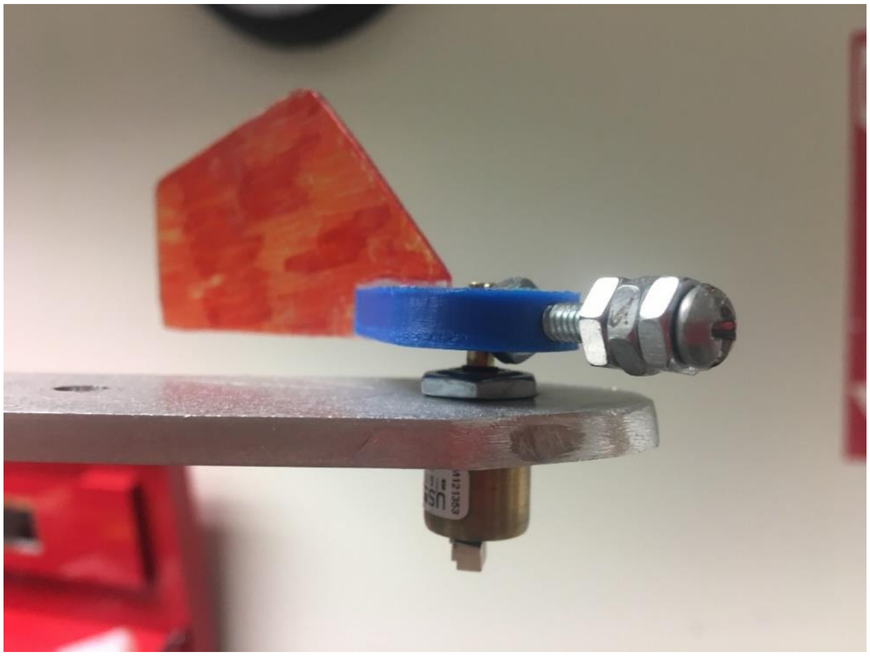


Figure 15: Wind Sensor

The mounting position of the sensor was chosen carefully. The higher the sensor on the main sail the better because of the stronger, more consistent winds. However, because the top section of our wingsail was determined to be detachable this was deemed not an option. The highest position we could mount it was toward the top of our bottom section. Mounting it in front of the leading edge was the best location as to avoid interference from the main sail. After researching airflow around the leading edge of a wing, it was discovered that up to four times the maximum thickness of the airfoil could be undesirable air flow for our sensor. We accordingly determined to mount the sensor 18" inches in front of the leading edge using an aluminum plank to better ensure accurate readings. With these readings, we formed a closed loop system.

Under the maximum lift setting, the angle of the tab continues to adjust until the main sail reaches the desired angle relative to the wind. After discussion with the SailBot team, we learned more about heeling angles and their effect on the speed of the boat. There are maximum heeling angles that the boat should stay under to maximize speed. The primary source of the heeling moment is from the lift of the wingsail. Therefore under maximum lift setting, the main sail should begin to lessen its angle of attack when the hull passes the desired heeling angle to retain the desired maximum. As the boat already has a gyroscope we decided rather than adding one of our own, that data should be received from the hull communications.

Mechanical Analysis and Design

Airfoil Selection

We chose an airfoil by going to www.airfoiltools.com and reviewing the catalogue of symmetrical airfoils. Symmetrical airfoils were deemed necessary because the wingsail was required to generate lift while at both positive and negative angles of attack. We looked through the airfoil catalogue and chose the airfoil that had the highest lift to drag ratio while maintaining a structurally sound shape. A Joukowsky transform airfoil was chosen with a maximum thickness of 18% of the chord.

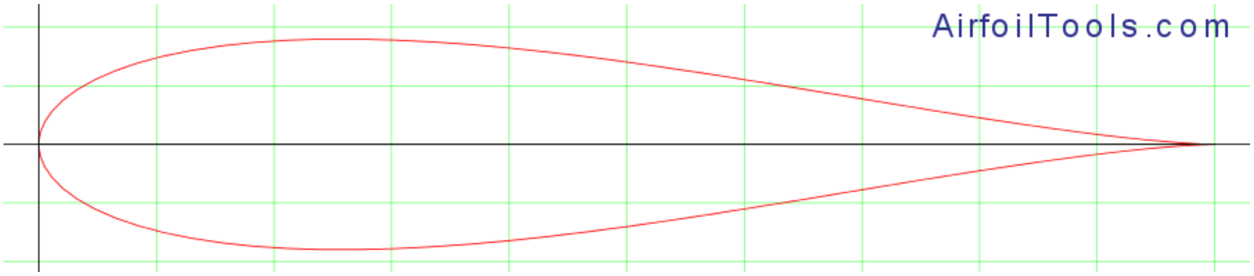
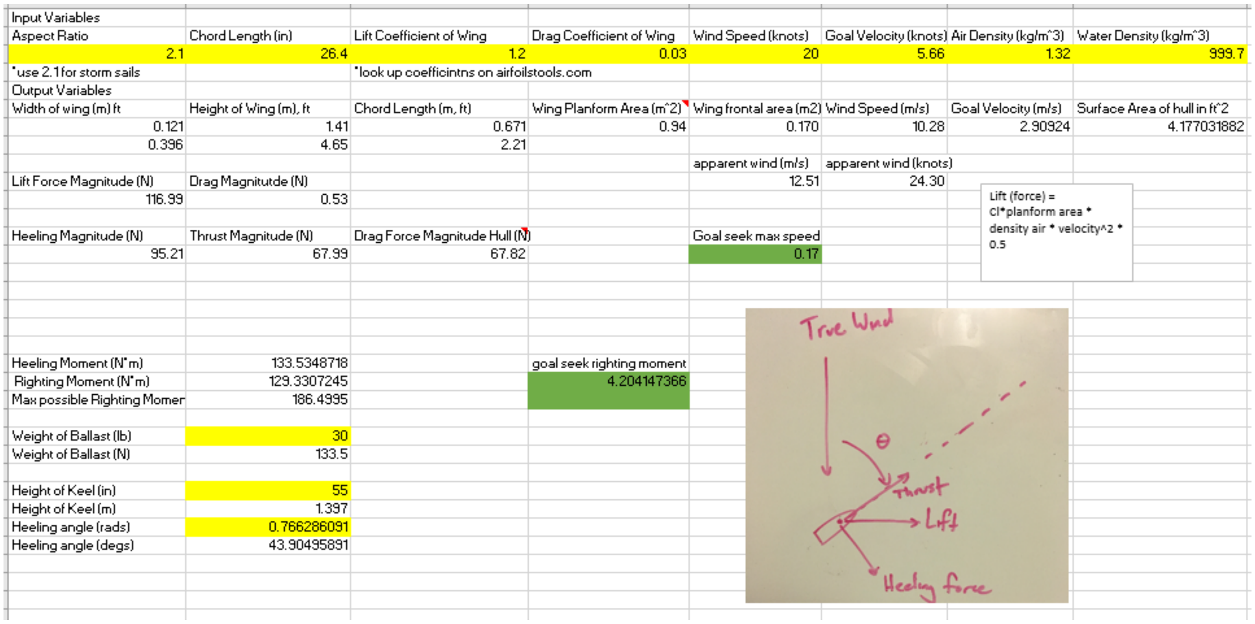


Figure 16: Joukowsky

Determining Wingsail Dimensions with Excel Simulation

We calculated the necessary size of the wingsail using an Excel document. The initial wingsail design was a simple rectangle with an airfoil cross section. The Excel document took the lift and drag coefficients, the main sail area, atmospheric properties, and hull resistance and calculated maximum boat speed, thrust, drag, and maximum heeling angle. A main sail height of 8.8’ was set to ensure that the overall height of the boat was approximately 1.5’ below the SailBot limit of 5 meters. This allowed the design room to grow in height as necessary and to allow for tolerances within construction. The chord length was also set at a maximum of 26.4” so that the airfoils could be laser cut on the WPI laser cutter. We iteratively increased main sail area using the maximum possible wind speeds until the maximum heeling angle of 45˚ was reached. Detailed Equations are in Appendix E.



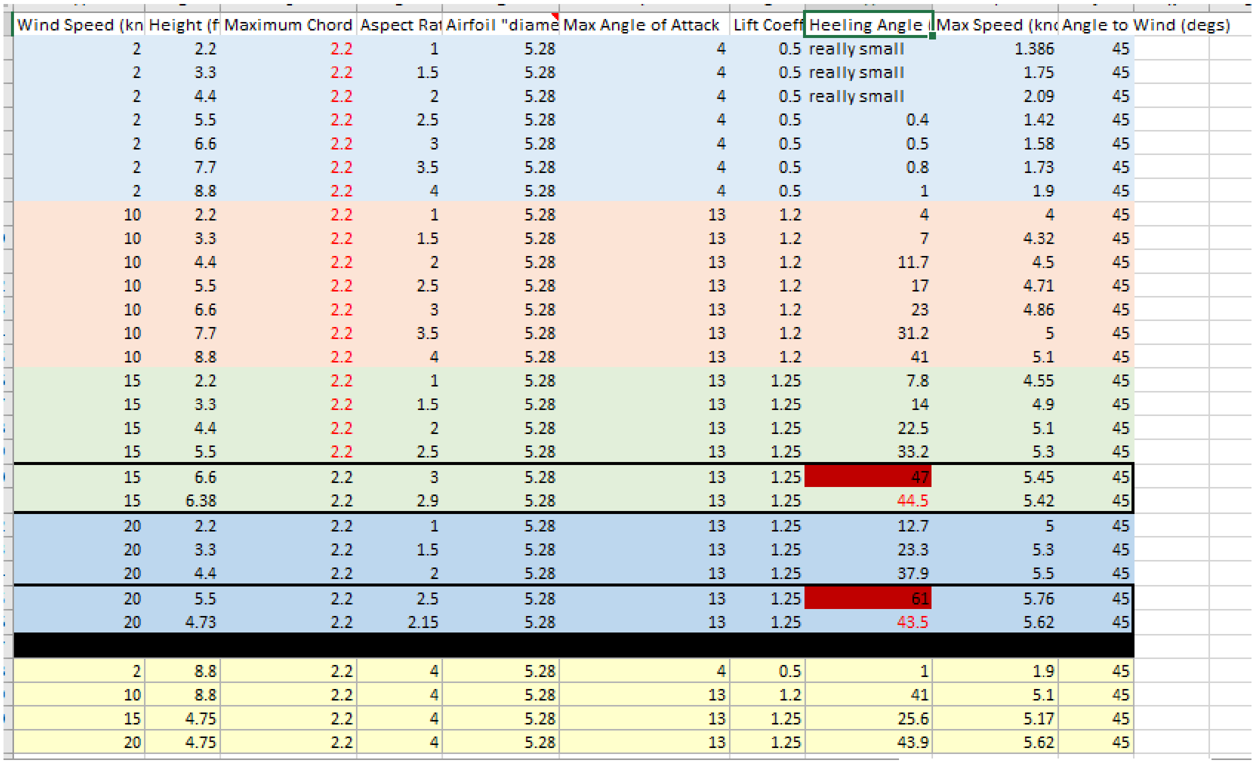
Input Variables							
Aspect Ratio	Chord Length (in)	Lift Coefficient of Wing	Drag Coefficient of Wing	Wind Speed (knots)	Goal Velocity (knots)	Air Density (kg/m^3)	Water Density (kg/m^3)
2.1	26.4	1.2	0.03	20	5.66	1.32	999.7
*use 2.1 for storm sails		*look up coefficintns on airfoilstools.com					
Output Variables							
Width of wing (m) ft	Height of Wing (m), ft	Chord Length (m, ft)	Wing Planform Area (m^2)	Wing frontal area (m2)	Wind Speed (m/s)	Goal Velocity (m/s)	Surface Area of hull in ft^2
0.121	1.41	0.671	0.94	0.170	10.28	2.90924	4.177031882
0.396	4.65	2.21					
				apparent wind (m/s)	apparent wind (knots)		
Lift Force Magnitude (N)	Drag Magnitutde (N)			12.51	24.30		
116.99	0.53						
Heeling Magnitude (N)	Thrust Magnitude (N)	Drag Force Magnitude Hull (N)		Goal seek max speed			
95.21	67.99	67.82		0.17			
Heeling Moment (N*m)	133.5348718		goal seek righting moment				
Righting Moment (N*m)	129.3307245		4.204147366				
Max possible Righting Momer	186.4995						
Weight of Ballast (lb)	30						
Weight of Ballast (N)	133.5						
Height of Keel (in)	55						
Height of Keel (m)	1.397						
Heeling angle (rads)	0.766286091						
Heeling angle (degs)	43.90495891						

Lift (force) = Cl*planform area * density air * velocity^2 * 0.5

Figure 17: Excel Simulation

We decided to make the top section of the main sail removable to optimize boat speed in all conditions. The bottom section of the main sail is optimized to operate between 10-20 knots and when the top section is added the main sail is optimized to operate between 2-10 knots. This ensured that in high winds the wingsail would not be able to generate excessive overturning forces and while in low winds, the wingsail would have enough area to propel the boat.

We again iterated through the Excel document for varying main sail areas and determined that the chord length should be 26.4”, the bottom section should be 4.75’ and the top section should be 4.05’ tall so that the main sail was 8.8’ tall.



Wind Speed (kn	Height (f	Maximum Chord	Aspect Rat	Airfoil "diame	Max Angle of Attack	Lift Coeff	Heeling Angle (	Max Speed (kn	Angle to Wind (degs)
2	2.2	2.2	1	5.28	4	0.5	really small	1.386	45
2	3.3	2.2	1.5	5.28	4	0.5	really small	1.75	45
2	4.4	2.2	2	5.28	4	0.5	really small	2.09	45
2	5.5	2.2	2.5	5.28	4	0.5	0.4	1.42	45
2	6.6	2.2	3	5.28	4	0.5	0.5	1.58	45
2	7.7	2.2	3.5	5.28	4	0.5	0.8	1.73	45
2	8.8	2.2	4	5.28	4	0.5	1	1.9	45
10	2.2	2.2	1	5.28	13	1.2	4	4	45
10	3.3	2.2	1.5	5.28	13	1.2	7	4.32	45
10	4.4	2.2	2	5.28	13	1.2	11.7	4.5	45
10	5.5	2.2	2.5	5.28	13	1.2	17	4.71	45
10	6.6	2.2	3	5.28	13	1.2	23	4.86	45
10	7.7	2.2	3.5	5.28	13	1.2	31.2	5	45
10	8.8	2.2	4	5.28	13	1.2	41	5.1	45
15	2.2	2.2	1	5.28	13	1.25	7.8	4.55	45
15	3.3	2.2	1.5	5.28	13	1.25	14	4.9	45
15	4.4	2.2	2	5.28	13	1.25	22.5	5.1	45
15	5.5	2.2	2.5	5.28	13	1.25	33.2	5.3	45
15	6.6	2.2	3	5.28	13	1.25	47	5.45	45
15	6.38	2.2	2.9	5.28	13	1.25	44.5	5.42	45
20	2.2	2.2	1	5.28	13	1.25	12.7	5	45
20	3.3	2.2	1.5	5.28	13	1.25	23.3	5.3	45
20	4.4	2.2	2	5.28	13	1.25	37.9	5.5	45
20	5.5	2.2	2.5	5.28	13	1.25	61	5.76	45
20	4.73	2.2	2.15	5.28	13	1.25	43.5	5.62	45
2	8.8	2.2	4	5.28	4	0.5	1	1.9	45
10	8.8	2.2	4	5.28	13	1.2	41	5.1	45
15	4.75	2.2	4	5.28	13	1.25	25.6	5.17	45
20	4.75	2.2	4	5.28	13	1.25	43.9	5.62	45

Figure 18: Excel Iteration

Later on in the project, we decided to add a taper to the main sail to increase aerodynamic efficiency. To do this, we calculated the maximum allowable taper while maintaining main sail area and not violating the 5 meter overall height limit. The final height of the airfoil covered main sail is 9.83'. The final dimensions are pictured in Figure 19.

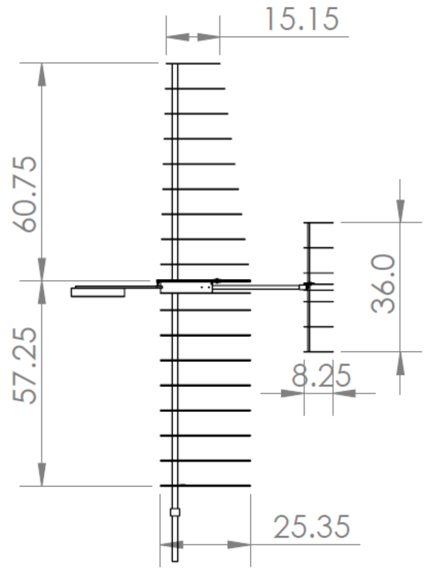


Figure 19: Wingsail with Dimensions

Mast

To narrow our mast selection, we first considered the shear and bending forces acting on the mast. The primary goal in mast selection was to reduce deflection of the mast to prevent warping of the airfoils. For our calculations, we considered the mast to be of constant diameter, and only considered the forces acting on the 6.6’ of airfoil covered mast, considering the bottom of the mast to be rigidly fixed. Forces acting on the bare mast were deemed negligible in comparison with forces generated on the airfoil covered main sail. As seen below in Figure 20, the force generated on the mast was considered to be equally distributed along the length as these values were calculated while tapering was not yet considered. Formulas used to derive the reactionary forces can be found in Appendix E

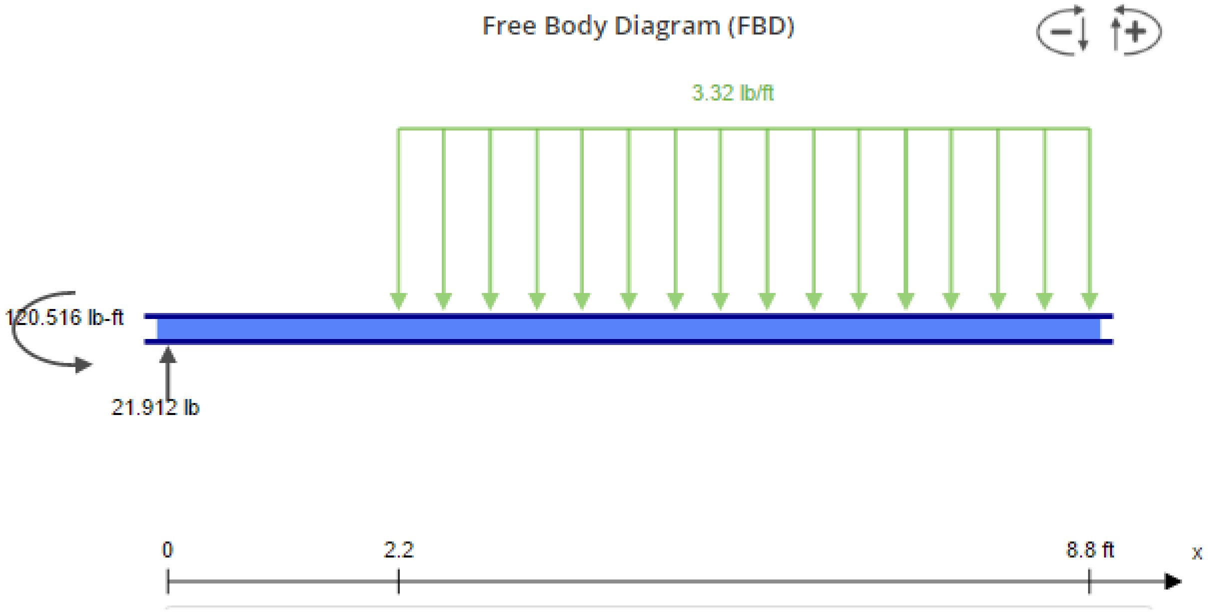


Figure 20: Free Body Diagram of Mast
Created Using SkyCiv Software

Maximum shear was calculated to reside at the non-covered portion of the mast at a maximum value of 21.91 lbs. Along the length of the mast, shear decreases to a zero value at 8.8'. Along the airfoil covered portion of the mast, shear force decreases linearly at -3.32lb/ft. From the shear force calculation, we concluded that our mast did not have to have constant rigidity and could in fact have decreasing stiffness along its length.

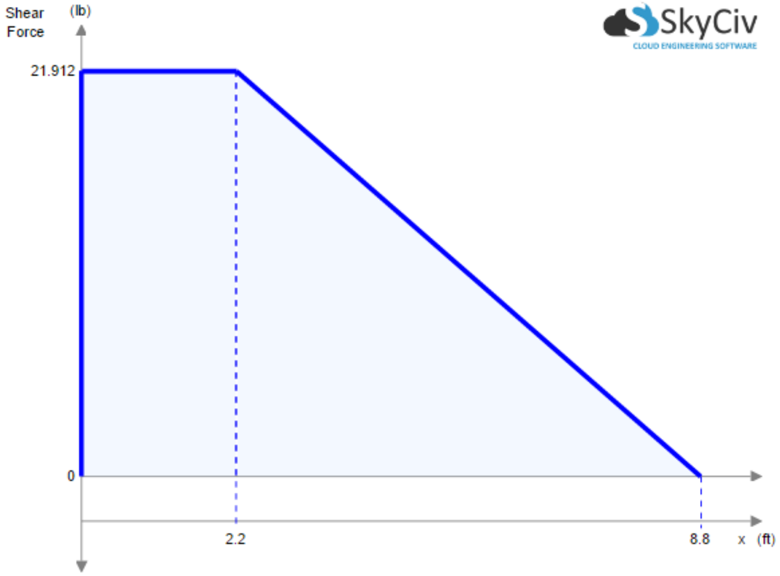


Figure 21: Shear Force Diagram
Created Using SkyCiv Software

$$Shear\ force\ (lbs) = S(x) = 21.912\ if\ x < 2.2$$

$$F(x) = 21.912 - 3.32x\ if\ x\ \geq 2.2$$

$$x = distance\ from\ base\ of\ mast\ in\ feet$$

Equation 2: Shear Force Equations

The bending moment of the mast is presented below in Figure 22. Along the non-covered portion of the mast, the bending moment decreases in value linearly. The portion of the airfoil covered mast has a parabolic bending moment ranging from 72.31 lb-ft to 0 lb-ft from 2.2' to 8.8' along the main sail. Maximum bending moment is seen at the point of fixture of the mast at a value of 120.52 lb-ft. This once again supports the need for a mast with a non-constant stiffness.

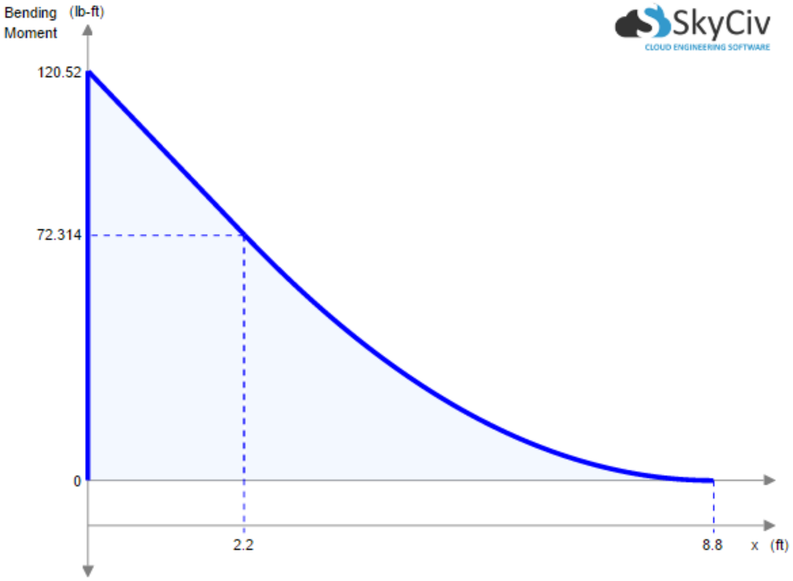


Figure 22: Bending Moment Diagram
Created Using SkyCiv Software

$$Bending\ Moment = B(x) = \ 120.52 - \int_{0}^{x} S(x)$$

Equation 3: Bending Moment Equations

When selecting a mast, we referred to our shear and moment calculations for stiffness requirements. Primary features when selecting a mast included weight savings, non-linear strength, height, and cost. We determined an RDM windsurfing mast would be the most feasible option in all of the listed categories. The selected mast was the Naish Sport RDM 430. The primary material in which the mast is composed is fiberglass. Windsurfing masts are given an IMCS, or Indexed Mast Check System, that can range from 0-22. The IMCS rating, which is always calculated based upon SI units, defines the deflection of the mast along the length as a given weight of 30kg is applied to the center of the mast (Sailworks, 2015). The formula to determine the IMCS rating is as follows:

$$\frac{Length1 * Length2 * Length3\ (cm^3)}{Mid\ Point\ Deflection\ (cm) * 216225}$$

Equation 4: ICMS Equation

Values of 0-6 refer to a hard top, 7-12 as a constant curve, 13-21 as a flex top, and 22+ as a super flextop. As the IMCS value increases so does the deflection at the top of the main sail where the diameter is at its lowest. The mast selected for this project has an IMCS value of 19, making it a flex top mast (Masts). Flex top masts have a "base-tip percent of mid-point difference in the 18%-22% range." The IMCS rating did provide insight into the potential deflection of the mast, however its loading differs from our implementation of the mast in that a point load is applied to the center and both ends are fixed, versus our evenly distributed load and single fixed end. Thus, we completed the following calculations to determine the deflection of the mast. The primary assumption made was that the mast is of a constant diameter to simplify calculations.

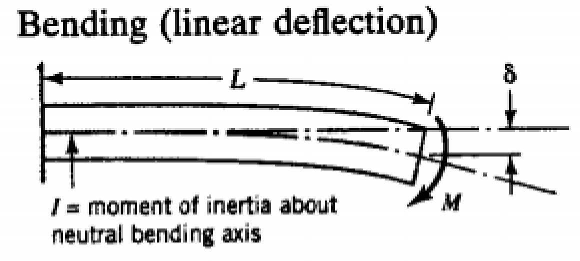


Figure 23: Bending (Linear Deflection)

The linear deflection δ is determined from the moment of inertia (M), length of the tube (L), Young's Modulus (E) and moment of inertia (I). Calculations for the moment of inertia are also given below. Under the same load of 3.32lb/ft, the maximum deflection at the end of the tube was determined to be 3.64in; the value was derived from the equations listed below. This value was considered to be acceptable as structural support from the airfoils further reduce the deflection.

$$\delta = \frac{ML^2}{2EI}$$

Equation 5: Linear Deflection

$$M = \frac{\pi(OD^4 - ID^4)}{64}$$

Equation 6: Moment of Inertia

The RDM mast has an internal diameter (ID) of 1.26" and outside diameter (OD) of 1.56" at the base (Networks, 2017). At the top of the main sail the ID is .98" and OD is 1.3". The total height of the mast is 14.1', however the used height is 11.6'. Approximately 21" were allowed for non-airfoil covered mast. There is 7" of above deck clearance, and 14" of below deck space.

Main Joint

We designed a main joint to contain the servo and hold the trim tab rod. This large joint also provided a convenient place to mount a forward protruding plank that mounts the wind sensor and the counterweight. This joint was placed at the top of the bottom section of the main sail because it allowed us to mount the servo in line with the trim tab, thus simplifying power transmission. Detailed drawings can be found in Appendix A.

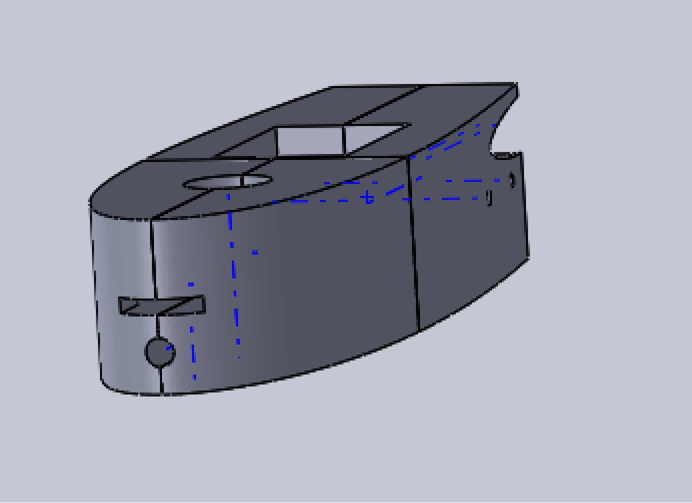


Figure 24: Main Joint View 1

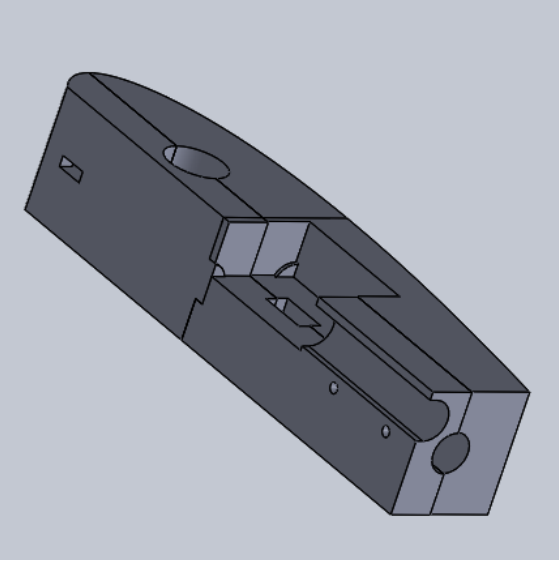


Figure 25: Main Joint View 2 with Cut-away to Show Interior

Bearings/Bushings

A bushing and bearing are used to facilitate free rotation. We calculated the torque that we expected the wingsail to produce under various wind conditions and designed a bearing system that did not require more torque than the wingsail could produce.

The equations used to calculate the torque are provided in Appendix E. See Figure 65 in Appendix A for a detailed drawing of the bushing.

Wind (m/s)	Wind (knots)	Torque From Tab (ft*lbs)
1.03	2	0.05
2.06	4	0.50
3.09	6	1.11
4.12	8	1.98
5.14	10	3.10
6.17	12	4.61
7.20	14	6.02
8.23	16	7.94
9.26	18	10.04
10.29	20	12.40

Table 7: Predicted Torque from Tab at Various Wind Speeds

Construction- Scale Models

Following the initial analysis and design, we constructed two scale models: a ½ and 15% model. The purpose of these scale models was to validate initial system analysis. The following sections review the construction primarily of the ½ model that was utilized to mimic the construction techniques needed to create the full scale model. A brief explanation of the manufacturing process for the 15% model is provided; said model contains no robotic components. Following this section, the testing and analysis of the scale models are provided.

15% Scale Model

We created the 15% scale model using a 3D printer. The model was small enough to print and the speed of the 3D printer allowed for rapid, simple creation and repair. The solid plastic also allowed us to drill small holes in the sides of the model to place telltales to determine when the main sail was stalled in the wind tunnel.

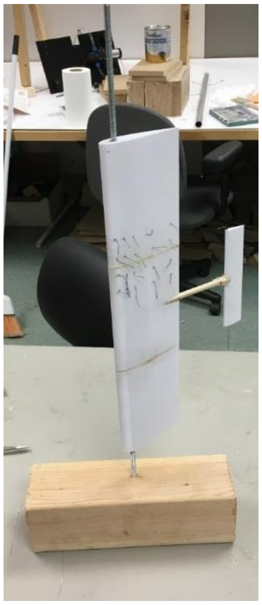


Figure 26: 15% Scale Model

½ Scale Model

Robotic Implementation

A purpose of the half-scale was to test the robotic components of the wingsail. For the ½ scale model the selection of the servo was simple and required a micro servo to test mounting and actuation under zero load because it would never be in the practical environment. The purpose was to test its actuation capabilities, as well as the limits of the push pull rod and its connectors. Appropriate paths were opened to allow for the running of necessary wires.

Mast

A curtain rod was bought from Home Depot to serve as the mast for the ½ scale. The curtain rod was chosen because it was the correct diameter, produced no deflection at testing loads, and was pre-cut to the correct length. We originally wanted to use ½” OD thin wall aluminum tube, however, this would have been more expensive than the curtain rod. We also did not have to pick a mast that mimicked the fiberglass mast perfectly because we had a high confidence in the fiberglass windsurfer mast, based on analysis provided in the *Analysis and Preliminary Design* section. It was assumed that if the mast could handle the force of a man sized windsurfer mast, with a human sized payload (150-200 lbs), it could handle the forces the 6.6’ boat (approximately 30-50 lbs) would generate. While this did not give us a chance to practice working with fiberglass, purchasing a fiberglass tube of the appropriate size would have been cost prohibitive.

Connecting Rods

The rod connecting the trim tab to the main mast was made out of a wooden dowel. This material was selected because we planned to use an aluminum tube for the full scale because of its light weight nature, machinability, and low cost (relative to carbon fiber). We did not use an aluminum rod of ½” scale size because finding aluminum of that size was not possible without ordering it and wooden rods were cheap and replaceable. Replaceable rods were important because we wanted the option to change the length of the rod depending on test results of the 15% scale model. Carbon fiber was also considered, but was rejected because of carbon fiber’s cost and potential for splintering.

A steel rod was used for the power transmission rod because we were considering using both a steel and a carbon fiber rod on the full scale. Steel rods are cheaper and easier to shape whereas carbon fiber rods are much lighter while retaining stiffness, but require the purchase/creation of a special joint since carbon fiber cannot be permanently bent. The ½ scale model served to demonstrate that for the full scale model we did indeed need to use a carbon fiber rod due to weight restrictions and applied forces.

Leading Edge

In order to attach the heat shrink wrap to the airfoils, a surface was needed along the leading edge of the main sail and trim tab. The leading edge served to create an aerodynamic surface in which air could flow over. Without the use of a leading edge surface the heat shrink wrap would shrink in between the airfoils. This phenomena is referred to as the “bat wing effect.” In order to prevent this from occurring, a material is placed over the leading edge of the airfoils, or around the nose of the wingsail where the curve transitions from convex to concave.

To create the leading edge, .03” thickness polycarbonate was utilized. Polycarbonate, also known by the brand name LEXAN, was selected because of its high Young’s modulus (348 Ksi), Tensile strength (10.9 MPa), and Compressive strength (11.6 Mpa). Polycarbonate is a thermoplastic of density .04 lb/in^3. To form the polycarbonate around the leading edge, we developed a male mold. This male mold was developed by laser cutting the leading edge of the airfoil with two holes located on the airfoil seen below. The airfoils were attached together and aligned via two steel rods running through the holes. Using the male molds, we then thermoformed the polycarbonate using a household oven.

Figure 27: Male Mold

There are multiple methods for thermoforming polycarbonate, including high and low temperature methods. High temperature methods require an extensive drying period, where the polycarbonate is heated at 257F for 15 hours and then allowed to sit at room temperature for 10-24 hours. Once the polycarbonate is treated it will form to the mold almost immediately when it reaches a temperature of 400F. Thermoforming at low temperatures requires no drying time, but the polycarbonate must be formed at a temperature no higher than 310F. Forming is estimated to take 20-40 minutes for polycarbonate of 0.03” thick. Our form with a leading edge radius of 0.375” took approximately 45 minutes to form. Pieces were 18” in length, by 7” in width.

Trailing Edge

A trailing edge for the main sail and trim tab were necessary such that the Monokote would not be pierced by the airfoil and to create a smooth edge at the tip of the airfoil. The trailing edge of the main sail and trim tab were constructed out of strips of .3" thick polycarbonate. The polycarbonate strips were measured to be 2.5" in width for the main sail and 1.25" in width for the trim tab. The polycarbonate was formed by initially cold forming the strips to have a crease along the length of the strip. To cold form, the strips were clamped along one edge lengthwise and then bent by hand where the crease was to be placed. A heavy steel cylinder was run along the crease with pressure until the polycarbonate retained its shape. To further define the crease and reduce the angle between edges, a heat forming technique was then utilized. A heat gun at the lowest setting of 430F was run along the crease and quickly followed by the steel cylinder with applied pressure. Utilizing both techniques created a smooth edge while matching the angle of the trailing edge of the airfoil.

Coating

To coat the ½ scale model we utilized Monokote for the top third of the main sail, and a heat shrink wrap for the lower two thirds of the main sail and the trim tab. We did not fully coat the ½ scale model with Monokote for monetary reasons. The heat shrink wrap, composed of a polymer plastic, had similar shrinking capabilities to that of the Monokote, shrinking at temperatures of 125F. However, the heat shrink wrap does not have tacking capabilities. To allow the shrink wrap to adhere to the airfoils, we applied the multi-purpose spray adhesive Super 77. After practicing with the shrink wrap we obtained a section of Monokote from the Aerospace department at WPI. To apply the Monokote, we first used a Top Flite sealing iron to adhere each of the corners. We wrapped the Monokote around the airfoil along the chord length of the main sail. To ensure the Monokote was taunt, after running the sealing iron along the airfoils, we used a heat gun at a temperature of 420F to obtain further shrinking. When the Monokote is not wholly taunt, ridges appear disrupting airflow over the main sail. For further details on the application of the Monokote to ensure a wholly aerodynamic surface see Appendix B.

With the remaining Monokote, we practiced creating entrance ports into the main sail. This was completed by creating a simple square out of scrap wood; the square being 12” by 12” in dimension. The Monokote was applied using the same technique stated above: first tacking the Monokote in each of the four corners, then around the outside perimeter, and finally creating a taunt surface by utilizing the heat gun. Clear packing tape was applied to the Monokote to create a square slightly larger than the desired port. The desired port size was 2.5” by 2.5” and the packing tape was applied in a section of 3” by 3”. Using a razor knife, a square port was cut in the packing tape; 0.25” were left on all sides between the edge of the cut and edge of the packing tape. One edge was left attached to the main sail to create a flap that could be taped down to create a seal. Access ports also play a role in the wingsail’s aerodynamic surface. Ports were designed such that they could be taped over during sailing, again assuring a smooth surface that does not affect airflow over the airfoil.

Testing and Analysis of Scale Models

15% Scale Model

A scale model of the wingsail at approximately 15% scale was constructed to meet a primary purpose of experimentation and validation. The scale model was placed in the wind tunnel located on WPI's campus to collect data on stall. The wind tunnel allowed for a constant airflow at a specified velocity over the model. The wind tunnel testing also allowed us to determine if the trim tab had enough authority to stall the main sail and various wind speeds. It was determined that at all speeds, from 2 knots to 20 knots (adjusted for the size of the model), the tab could indeed stall the main sail.

$$\mathrm{Re} = \frac{\rho u L}{\mu} = \frac{u L}{\nu}$$

Equation 7: Reynolds Number Calculations

- ρ = density of fluid
- u = fluid velocity
- L = characteristic length
- μ = dynamic viscosity
- ν = kinematic viscosity

The above equation indicates that the Reynolds number is directly proportional to the characteristic length (in this case the length of the chord) and velocity of the wind. Thus, to simulate the effects of a certain Reynolds number, we set the wind tunnel to produce wind 6.66 times larger to compensate for the smaller characteristic length of the model (0.15). For example, to replicate the effects of a 2 knot wind on the full scale, we subjected the 15% model to about 13 knots. We were able to set to the wind tunnel speed accurately to +/- 0.2 knots.

Wind Tunnel Speed (knots)	Relative Speed for Full Scale Model (knots)
13.32	2
26.64	4
86.58	13
133.2	20

Table 8: Table of Wind Tunnel and Relative Speeds

½ Scale Model

The ½ scale model was too big to fit in a wind tunnel so all testing was conducted outside using natural wind. The primary purpose of the ½ scale model was to validate the construction techniques; however, it was also used to verify that the trim tab had enough authority to turn the main sail in low winds, as we had mathematically calculated. Although this was already determined via the wind tunnel test, the ½ scale testing served as a second source of validation.

To test this, the ½ scale model was mounted to a rotating stool and taken outside to test in realistic, inconsistent wind conditions. The trim tab was set to various angles (10-45˚) and visually monitored to see if the main sail rotated. While this test was not precise, it did give us an approximate indication of whether or not the trim tab design needed to be changed. We determined no alternation needed to be made to the trim tab design.

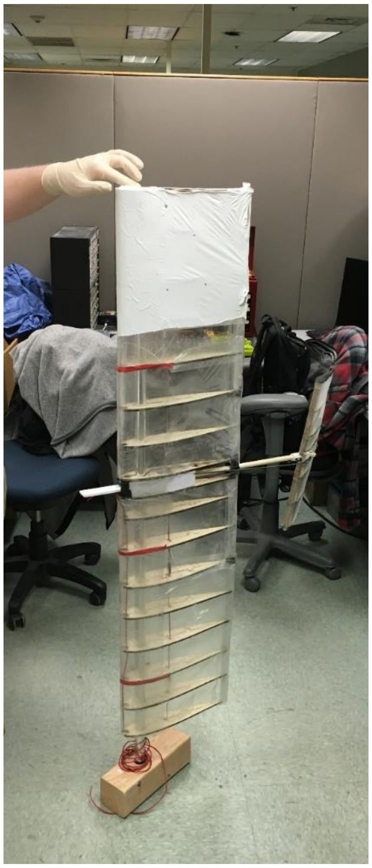


Figure 28: 1/2 Scale Model

Construction and Robotic Development- Full Scale

Upon completion of the creation and testing of two scale models, we retained validation of our initial design analysis, only making minute alterations to our design. We next moved on to the construction of the full scale system and later, the final testing and validation of the full scale wingsail.

Robotic Development

Communications and Power

Our expectation of the slip ring led us to make certain decisions such as modifying our mast selection to ensure it fit the slip ring, choosing the Teensy 3.6 due to its CAN ports, and the choice of NMEA2000 standards. Due to the slip ring's large size and waterproofing however, the slip ring had far too much friction to allow for the free rotation of the main sail in the boat. As a result, the NMEA2000 standard, at least for the communications between the wingsail and the boat, was scrapped. Even though we no longer needed the CAN port, the Teensy was already purchased and still served all of our needs. Similarly, we had already purchased our new selection of the mast.

With no feasible option of wired connection from the hull to the wingsail, a wireless connection was now the only option. Because the SailBot team would be the ones dealing with this connection on the primary end, the decision was left up to them. Due to the boat already communicating to shore via WiFi, the decision was made to use the same method for communication with the wingsail. The SailBot team decided on using the ESP8266 as a WiFi serial pass through.

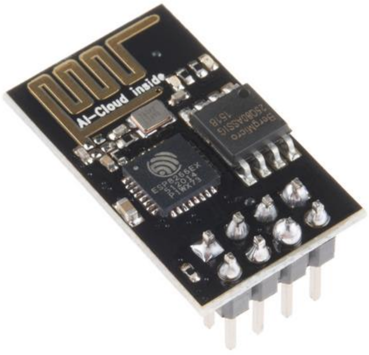


Figure 29: ESP8266 Wi-Fi Module

The placement of the Teensy was planned on the bottom rib of the main sail, not because of weight, but mainly because the communications wire from the slip ring would be closer to the controller. Due to the Teensy's low weight of 0.2 ounces, mounting it closer to the servo location toward the top of the bottom section of the main sail allowed for the running of less wires from the bottom; reducing running seven wires to only two.

The NMEA2000 standard also included power. Since there was no longer a wired connection, batteries had to be added to power the wingsail. The highest voltage requirement came from the servo at 6 volts. Using rechargeable LiPo batteries was the first idea, however, it required always having one or two spare batteries charged where there may not be access to an available power source. By using standard AA or AAA batteries there would be no need to recharge and could be readily stored and obtained. The batteries are mounted at the bottom rib of the main sail to keep weight lower, therefore a positive and negative wire are run up to the Teensy and Servo for power.

Hardware

The Teensy and WiFi board are contained in a 3D printed case. To ensure the case and its contents can be removed from the main sail, screw terminals were added to the outside of the case. The Servo and Teensy both run off of 6 volts coming directly from the batteries. The teensy outputs a regulated 3.3 volts that the WiFi board and wind sensor run off of. After the internals were soldered and completed, four LEDs were wired in and added to the external of the case for display purposes. The goal was to seal the case upon its completion to keep it water resistant. The screw terminals added provided connection from the board to its peripherals.

Screw Terminal	**1**	**2**	**3**	**4**	**5 and 6**
Purpose	Servo Signal	Wind Sensor Signal	6 Volts	3.3 Volts	Ground
External Connections	Servo Signal	Wind Sensor Signal	Battery Positive and Servo Positive	Wind Sensor Positive	Servo Ground, Battery Ground, and Wind Sensor Ground

Table 9: Terminal Connections

The remaining capability that had to be accessible after sealing was programming. This required two aspects, the USB cable plugged into the teensy itself, and the button that needs to be pressed to enter programming mode. A short USB cable was inserted through the case and an external button was wired to the programming button that can be pressed with a screwdriver as to avoid accidental pressing. These additions were made to avoid having to open the case under standard circumstances to keep out corrosive saltwater.

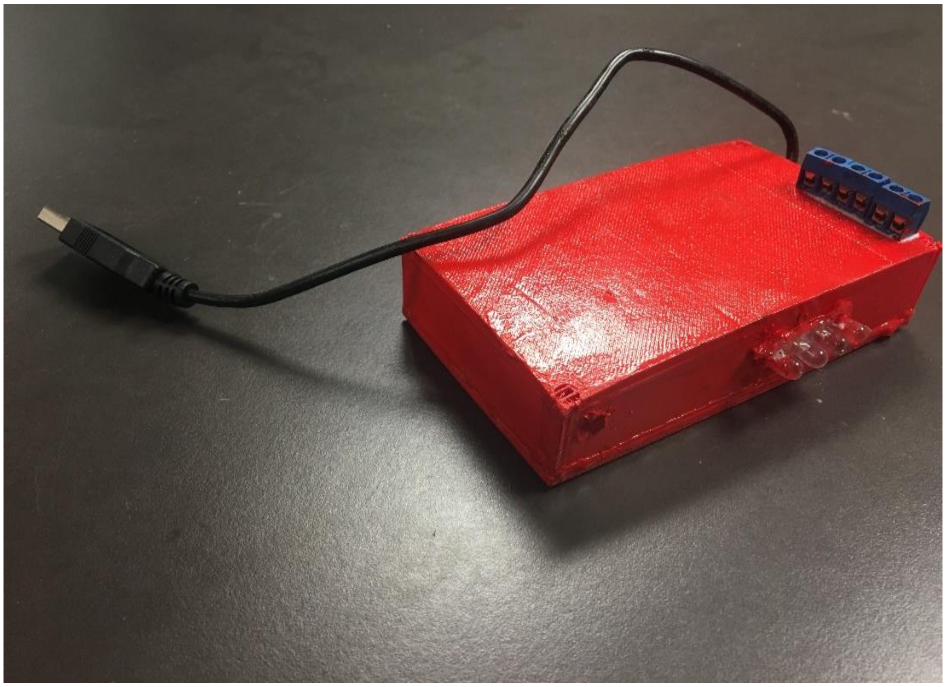


Figure 30: Self Contained Main Sail Electronics

Code Design

Further capabilities were added in the programming of the wingsail as more desired features were realized. Primary states of the wingsail were updated to four. These include: maximum lift and minimum lift, and the introduction of maximum drag and manual control. Maximum lift is ideal for going up wind and cross wind. It uses the closed loop system to maintain the main sail at the desired angle of attack, only lightening up to maintain the maximum desired heeling angle. It has the option of port and starboard depending which direction the wind is coming from relative to the boat to achieve lift in the correct direction. Minimum lift is ideal when wanting the boat to stay still. The wingsail runs the same closed loop system, instead with a desired angle of attack of zero. The goal of maximum drag is to achieve more drag than lift to move the boat on a downwind path. The wingsail is not ideal for downwind and will most likely implement a form of jibing to obtain the fastest downwind movement. In maximum drag setting the servo will go to max deflection to ensure the main sail is in full stall conditions. This setting also has port and starboard options. Lastly, the introduction of manual control was added upon request from the SailBot team. The angle of the tab is able to be directly controlled through the communication with the hull.

With the introduction of wireless communication there is a possibility that the connection may be interrupted for various reasons. If connection is lost, the wingsail will default to the minimum lift mode. This is to prevent the boat from sailing off in an unpredictable direction. Methods were researched to further failsafe the wingsail against loss of power, such as an electromagnetic clutch and a backup battery. This method was considered too late into the project. An electromagnetic clutch would require significant redesign on our mounting of the servo. The electronics were not designed with the plan of the backup battery and would have to be restructured.

The main code that controls the actuation of the wingsail is run in the main loop. Each cycle of the loop would adjust the angle of the servo by 1˚. As to avoid immediate adjustment to possible stray wind conditions a delay is integrated with the code to act as a low pass filter, lowering the frequency of the sensor readings and reactionary adjustments.

Upon the integration of the code with the Wi-Fi portion, there was a significant delay in the sensor readings and reaction time of the code. To work around this, the entire control code was put into a timer interrupt. This allowed the Wi-Fi signals to still be received and processed while also allowing for the loop controlling the wingsail to run at specified intervals. This was the best method to accomplish this as the time to run the control code is negligible and it gives a simple method for adjusting the reactivity/stability time which is the timer interrupt.

State Display

Now that the wingsail is controlled via Wi-Fi, we deemed it important to be able to visually identify the wingsail's current functions. Using LEDs we were able to correlate various combinations with important states of the wingsail’s operation.

The wingsail contains four LEDs, one white, one yellow, one red, and one blue. These colors were chosen as they are easily distinguishable. The blue LED is a power indicator. The white LED is to display the wireless connection to the hull. When the LED is off it has no connection to the access point, when blinking, the wingsail is connected to the access point but not the TCP port for communication, and when the LED is constant on the wingsail is connected.

The yellow and red LEDs are to display the current state of the wingsail. The yellow LED represents the wingsail being in maximum lift mode while the red LED means the wingsail is in maximum drag. If the yellow LED is constant, it means the wingsail is in maximum lift with the wind coming from port, while the LED is blinking the wind is coming from starboard. This method is mimicked for the blue LED and the maximum drag mode. When both LEDs are off the wingsail is in minimum lift mode, and when both are on the wingsail is under manual control from the hull.

	Red LED	Yellow LED	White LED	Blue LED
Off	Off	Off	Off	Off
On with no access point connection	Off	Off	Off	On
On with no connection to the program port	Off	Off	Blinking	On
Minimum Lift	Off	Off	On	On
Maximum Lift (Port)	On	Off	On	On
Maximum Lift (Starboard)	Blinking	Off	On	On
Maximum Drag (Port)	Off	On	On	On
Maximum Drag (Starboard)	Off	Blinking	On	On
Manual Control	On	On	On	On

Table 10: LED Indication Table

Mechanical Construction

Bushings/Bearings

Our team machined a bushing out of Delrin to go into the top the fiberglass tube. Delrin was chosen because of its low coefficient of friction and its workability. Purchasing a conventional bearing was considered however, the OD of the mast and the ID of the PVC are non-standard dimensions, 1.52" and 2.075" respectively. The SailBot MQP used an off the shelf bearing and we manually machined the Delrin plug at WPI. The mast of our wingsail sits in a PVC tube that is glassed into the hull of the boat. The SailBot MQP team designed a bearing and a plug system to secure the bottom of the mast and allow free rotation. The mechanical drawing of the bushing is seen below.

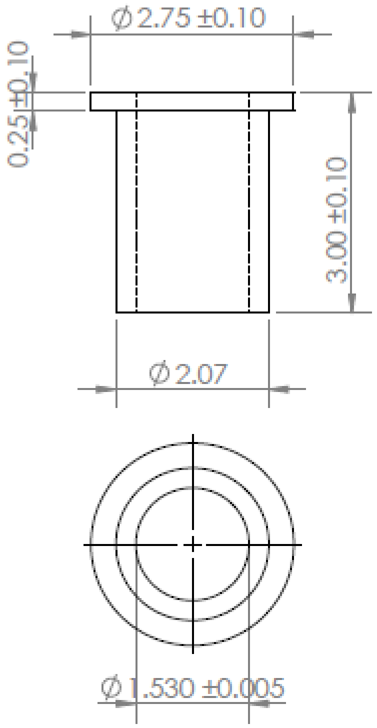


Figure 31: Bushing Design

Shaft Collar

We decided to use a shaft collar in combination with a retaining piece designed by the SailBot MQP to vertically constrain the mast. This prevents the mast from falling out in the event of a capsizing. See Figures 32 and 33 for more detail.

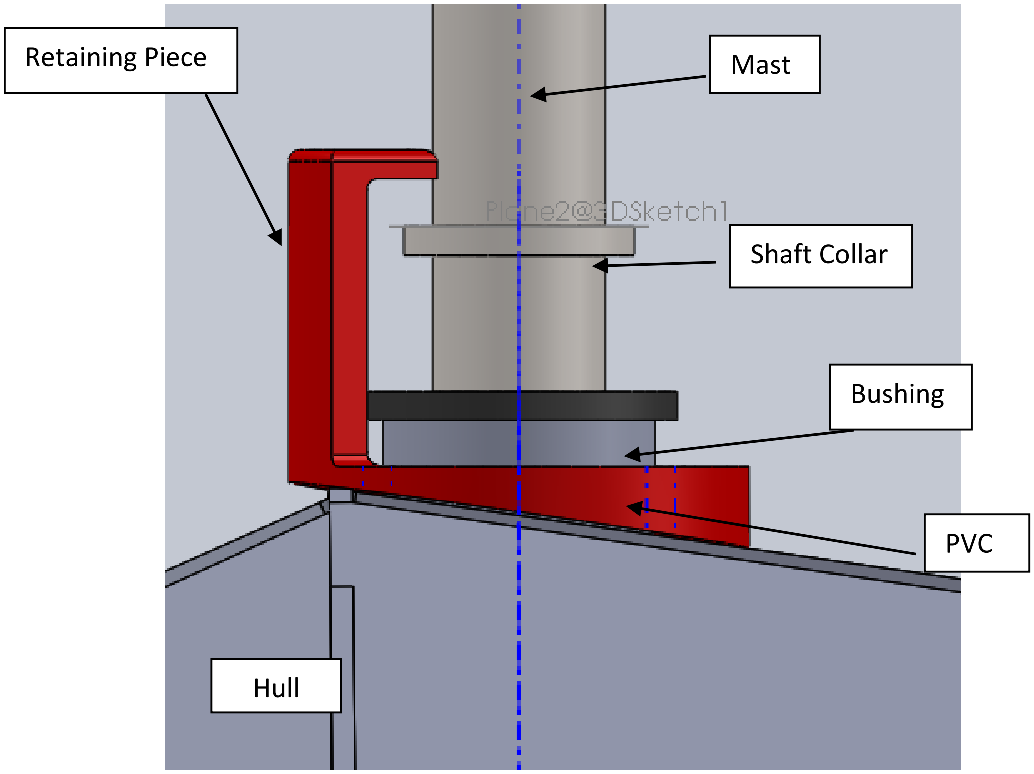


Figure 32: Bearing Installed in Hull

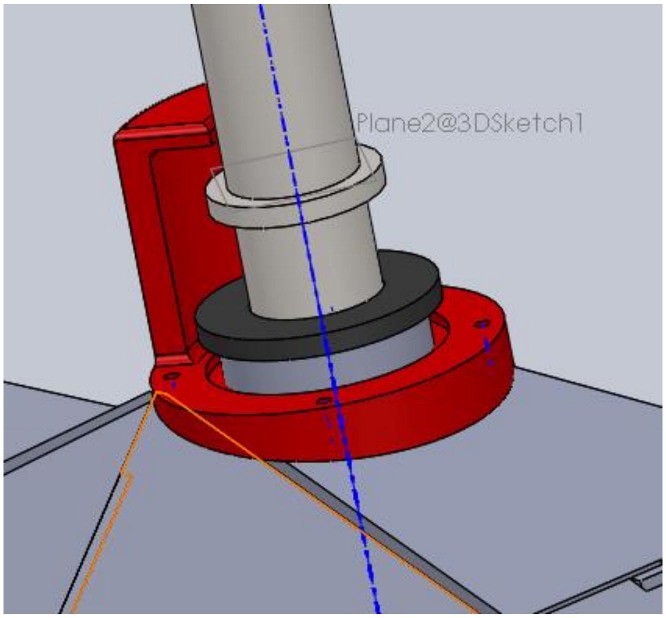


Figure 33: Bearing Installed in Hull 2

Joining the Top and Bottom Sections of the Main Sail

To ensure that the top and bottom sections of the main sail cannot rotate independently of each other and stay pressed firmly together, a "button" device was designed. See the image below in Figure 34 for details. The two pieces of the button are held together by a nut, bolt, and a washer. When the button is pressed together, it ensures that the two section of the wingsail rotate together and that they do not fall apart in the event of a capsizing. In addition, the male-female joint of the mast is robust and contributes to the constraining of the main sail.

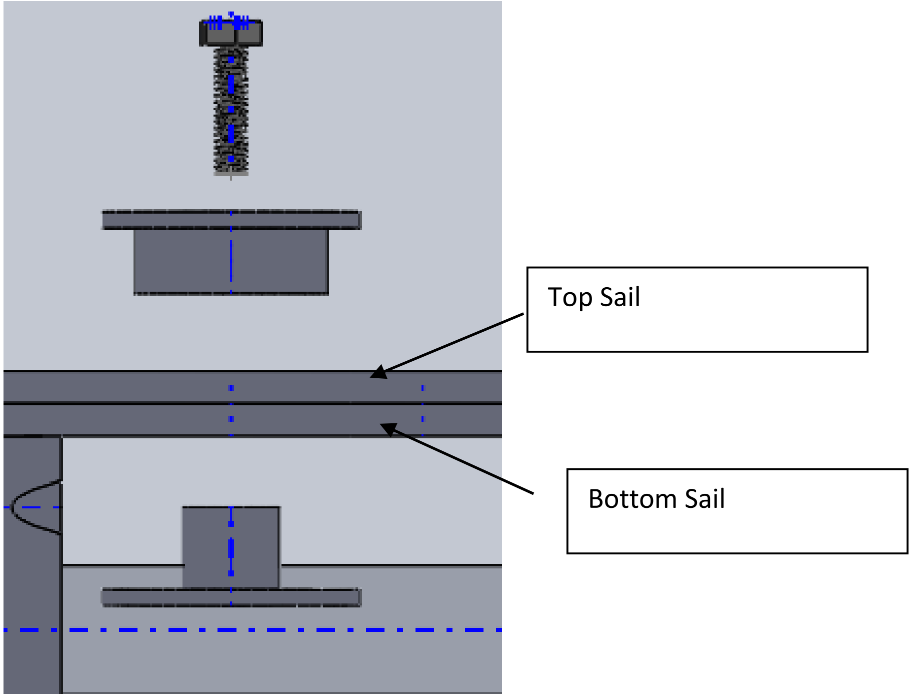


Figure 34: Exploded View of Button

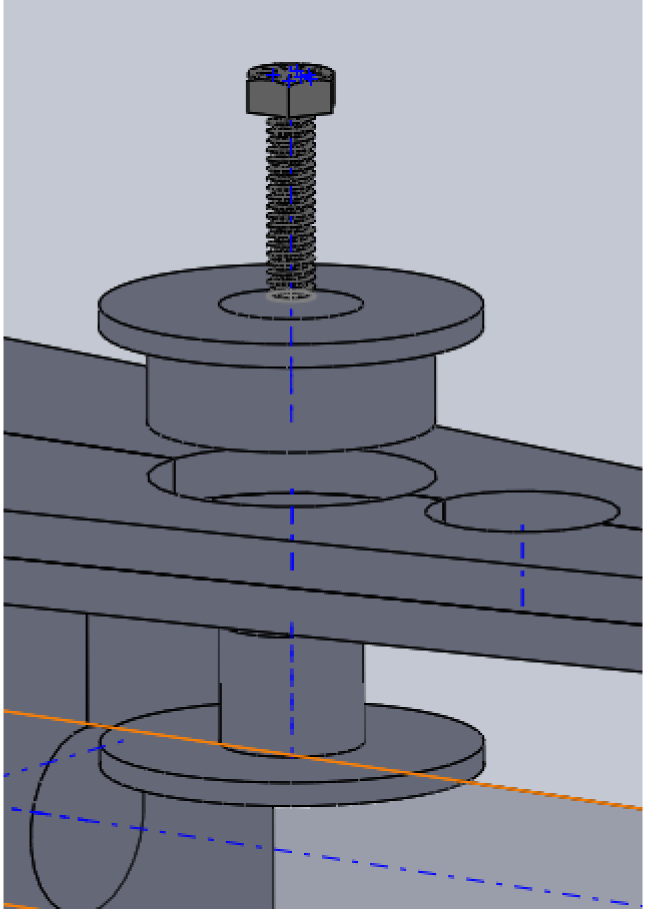


Figure 35: Exploded View of Button Isometric

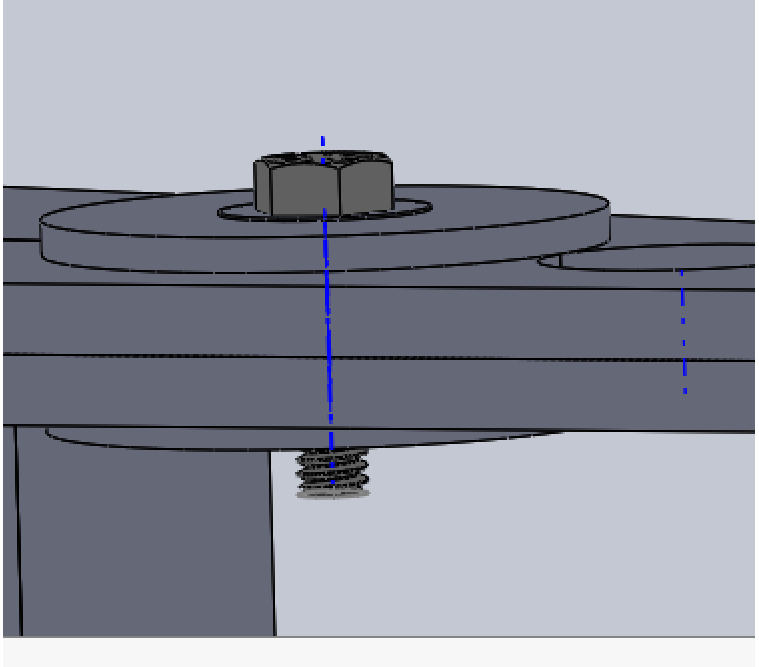


Figure 36: Pressed Button

Skeleton

From our test results, we were satisfied with the performance of ribs used in the ½ scale model. Thus, we made very few changes to the design of the airfoils other than scaling them up. No changes were made to the bottom section airfoils other than making them bigger.

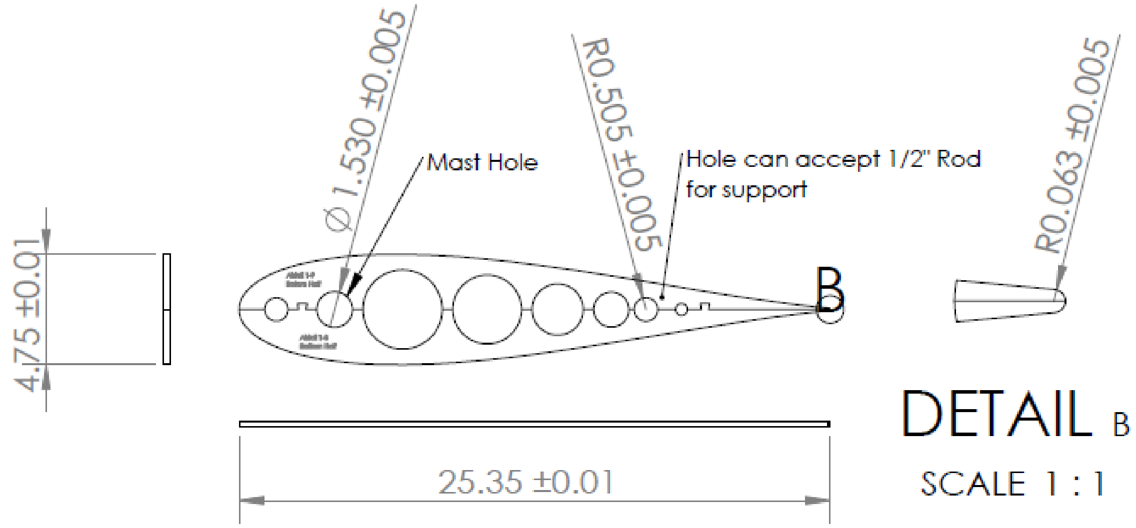


Figure 37: Lower Wing Airfoils

Adjustments were made to the design of each tapered airfoil on the top section of the main sail so that there was one ½" hole and one 1" hole on each airfoil that lined up vertically. This was done to allow the placement of a reinforcing ½" or 1" rod if necessary. The mast had to be carefully measured as the mast tapered in a non-linear manner. Thus, the hole diameter for the mast varies from airfoil to airfoil. Detailed drawings of each tapered airfoil are in Appendix A.

The ribs were laser cut using the WPI laser cutter. The airfoil ribs of both the main sail and trim tab were constructed out of ¼" pine plywood. The ribs were then glued to the windsurfer mast using two part epoxy. The vertical location of the ribs were marked with sharpie before gluing. The ribs were aligned rotationally by running ½" rod through the ½" holes in the rib. We only glued 2-3 ribs at a time to allow us to check the alignment by eye throughout the drying process.

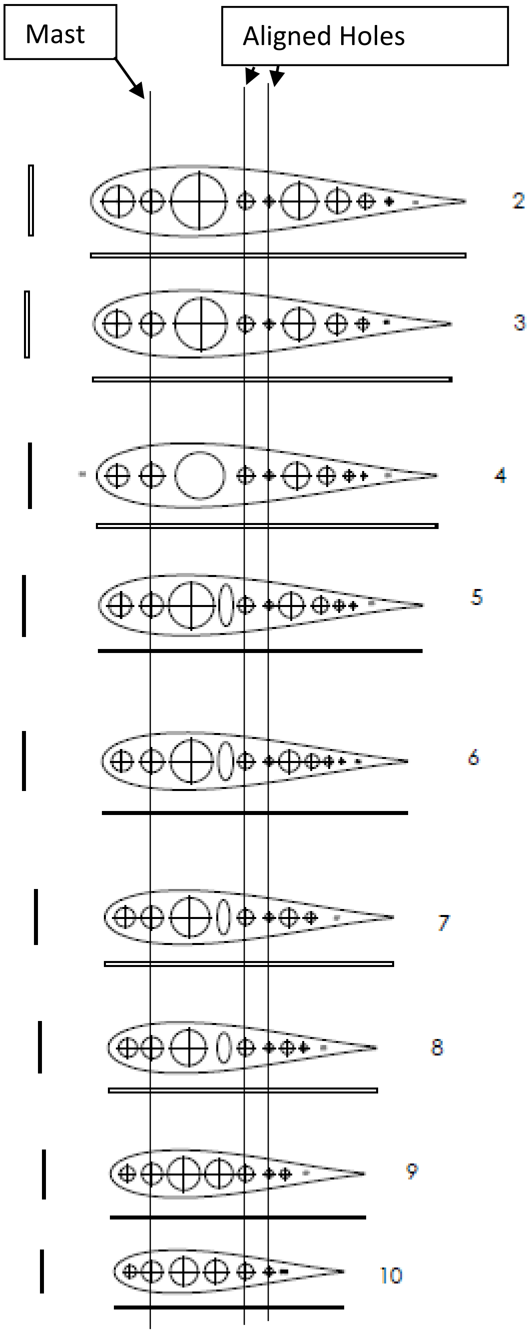


Figure 38: Tapered Airfoils Overview

The servo access airfoils were not modified except to scale them up to fit the full size wingsail.

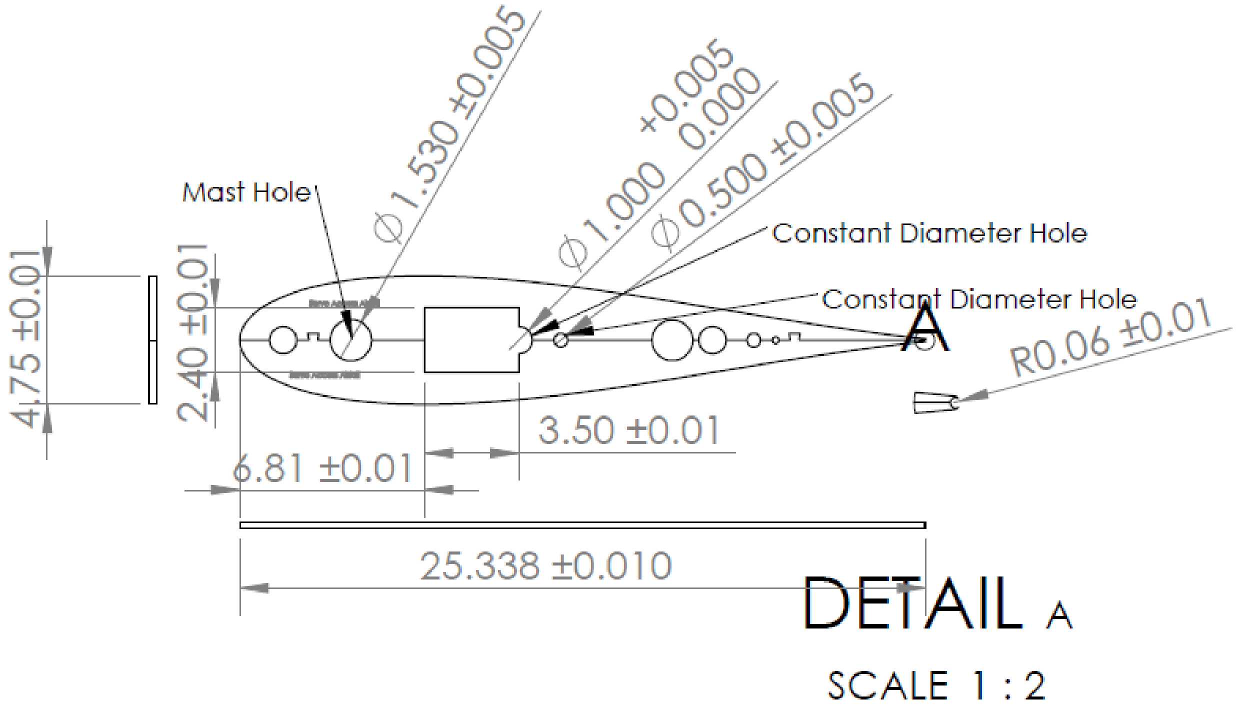


Figure 39: Servo Access Airfoil

The trim tab airfoils were not changed significantly. The only changes were to the weight saving cut outs, which were slightly reduced in size and moved to eliminate weak points in the rib.

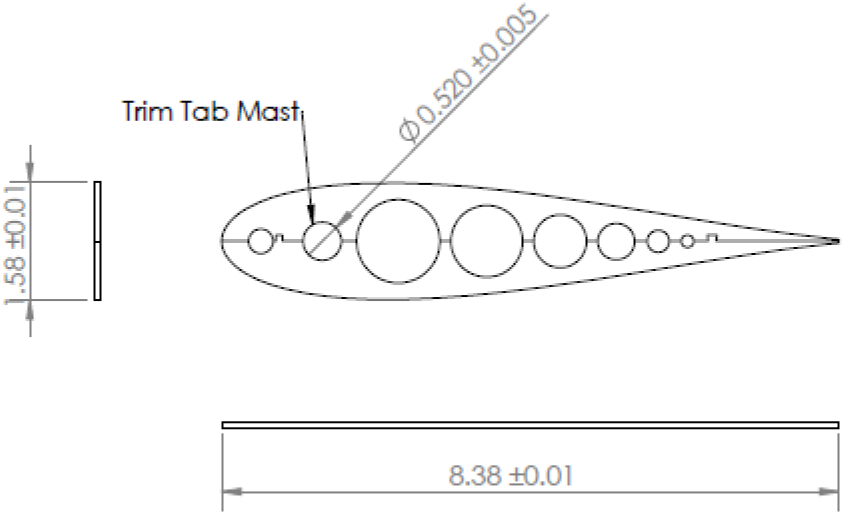


Figure 40: Trim Tab Airfoil

Trim Tab Actuation System

The push pull rod method used in the ½ scale model worked well and we created a CAD simulation to ensure that the tab servo connector and the servo cap were the correct dimensions to allow for +/- 45˚ of trim tab actuation. Detailed drawings of the servo cap and the tab servo connector can be found in Appendix A. The distance between the two pivot points is 33.13”.

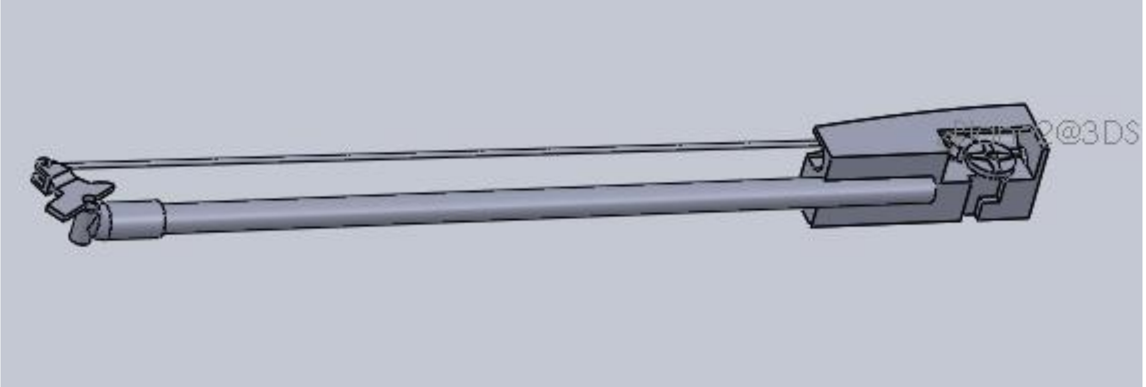


Figure 41: Push Pull Simulation

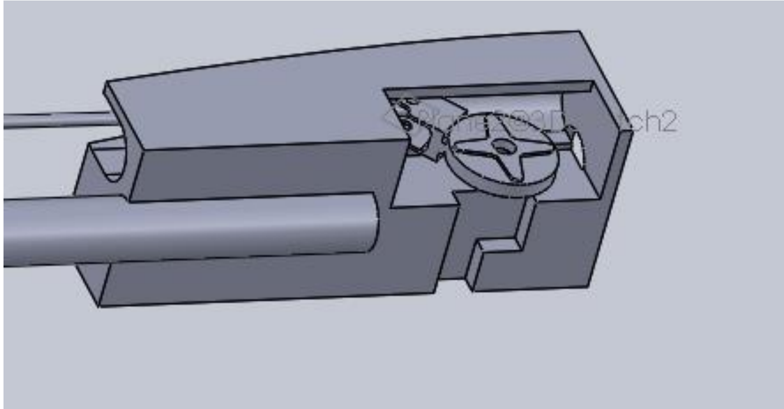


Figure 42: Push Pull Main Joint

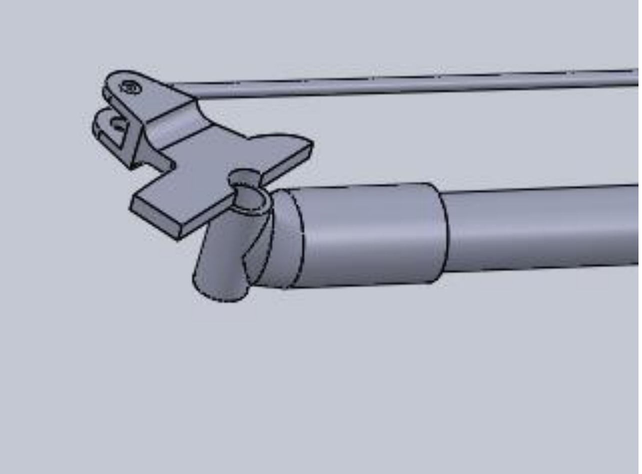


Figure 43: Push Pull Tab Joint

Leading Edge

To create the leading edge for the full scale wingsail, balsa sheeting reinforced with fiberglass was utilized. Balsa was selected due to its formable, lightweight nature. The balsa sheeting was custom ordered to fit the leading edge of the main sail to ensure folds would not occur in the Monokote. The balsa ordered was .05” thick, 18” in width, and 36” in length. For the trim tab, the sections order were .05” thick, 7” in width, and 36” in length. The grain of the balsa runs along the length of the sheets to prevent cracking while forming. To apply the balsa sheets a layer of 5 minute epoxy was applied to the leading edge of the airfoil and one side of the balsa was wetted until the sheets began to curl. The balsa sheets were laid over the airfoil, making sure the centerline on the sheet lined up with the highest point of the leading edge arc. We smoothed the balsa using our hands to ensure the sheets perfectly aligned with the leading edge to preserve the geometry of the airfoil.

After the balsa was applied and allowed to dry, fiberglass cloth was applied to reinforce the strength of the balsa. Two layers of 3.6oz fiberglass cloth coated with hardener were utilized. This selection in fiberglass came at the recommendation of Professor Linn, who stated that these are the standard materials and methods when creating model aircrafts. The fiberglass cloth was draped over the leading edge of the airfoil and cut to size; .5” of overhang was allowed on all edges of the airfoil. Once the first layer of fiberglass cloth was draped, a resin and hardener mixture was applied over the cloth. The second layer of fiberglass was then draped, the grain of the cloth running along the opposite direction as the first layer to maximize strength (considering the difference in bend and warp). We smoothed over the fiberglass using our hands, allowing the second layer of cloth to soak up excess resin and hardener mixture to preserve additional weight. Material properties of the fiberglass considered during application are listed below.

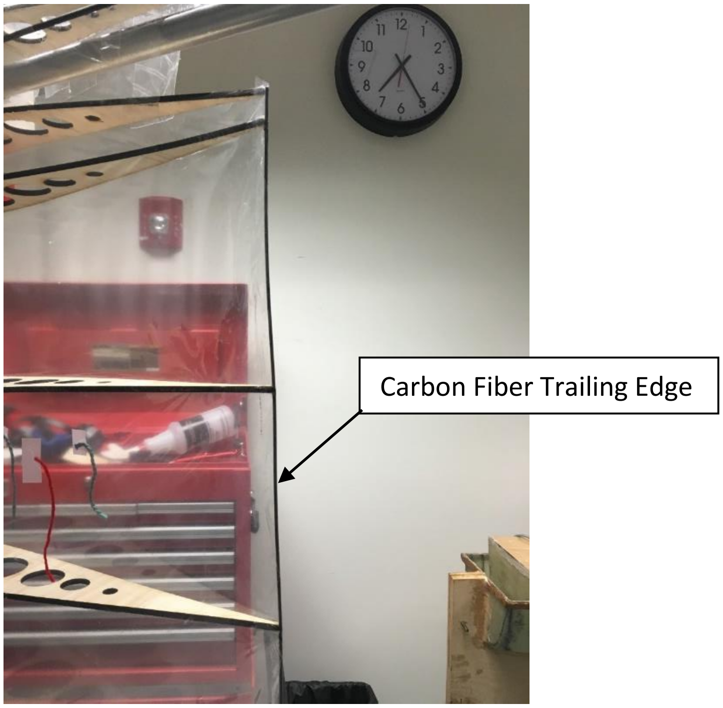
3.6oz Fiberglass Cloth	
Strength (Warp)	65 lbs/inch
Strength (Fill)	60 lbs/inch
Thickness	.0059”
Weight	3.64 oz/yard

Table 11: Fiberglass Material Properties

Once the fiberglass and mixture had dried completely, the edges of the fiberglass were trimmed using a razor knife. The leading edge was sanded using 100 grit sandpaper to remove any large imperfections such as lumps of fiberglass that would disrupt airflow. This technique was used to create the leading edge of both the main sail and the trim tab.

Trailing Edge

To reduce the time needed to create the trailing edge of the main sail and trim tab, as well as create a more linear edge for the Monokote to lay, we decided to utilize carbon fiber rods. The rods were chosen to closely match the diameter at the tip of the trailing edge of the airfoil and based on what was available for sale. For the main sail, we chose the carbon fiber rod based on the consistently sized airfoils at the bottom section of the main sail. For the main sail the rod diameter is .098" and for the trim tab the diameter is .08". The airfoils were altered such that at the trailing edge of each airfoil a half circle was cut to match the dimensions of the carbon fiber rods. The primary purpose in utilizing the carbon fiber rods was to create a finite tip of the airfoil to ensure proper merging of the airstreams traveling along the airfoil, while ensuring the Monokote would not be pierced. An image of the trailing edge is depicted in Figure 44.



Carbon Fiber Trailing Edge

Figure 44: Trailing Edge

Coating

For the full scale model, Monokote was utilized as the covering for both the main sail and the trim tab. The Monokote was applied in sections along the length of the wingsail, versus along the chord of the airfoil as in the ½ scale model. Two sections were needed to cover each half of both the trim tab and main sail. Methods for proper application of the Monokote can be found in Appendix B. Once the Monokote was initially attached, the sealing iron was run along the leading edge of the main sail and the edges of the airfoils to preserve the airfoil shape. Along the trailing edge, the Monokote was run around the carbon fiber rod and adhered using the iron. Proceeding, the heat gun was used to ensure the Monokote was taunt and without any ridges visible. The space between the airfoils not covered by the fiberglass was particularly concentrated on using the heat gun as these were the points where ridges formed that could cause issues in airflow. The Monokote was applied to the trim tab using the same methodology.

When covering the ends of the main sail and the trim tab, a section of Monokote was cut to match the airfoil profile. These sections were adhered using the sealing iron and connected to the overhanging portions of the previously applied panels of Monokote. The heat gun was not used on these ends. To create the port holes the same method used during the ½ scale was utilized. Packing tape was applied to the section where the desired port hole would be placed, ensuring at least .25” from the edge of the cut to the edge of the tape. Using a razor knife, the port hole was then cut, leaving one edge attached to the Monokote to create a flap that could be sealed when needed.

Counterweight System

After observing the ½ scale, it was determined that a counterweight was needed to ensure that the wingsail would not rotate due to gravity when the boat heels. Through experimental testing, it was determined that a counterweight of 3.4 lbs was necessary for the wingsail to be perfectly balanced. Testing included laying the wingsail horizontally and balancing it between two chairs. Weight was added to the plank using a spring scale until the wingsail came to be wholly level. To ensure that the wingsail was perfectly balanced, a level was rested on the body of the wingsail. This testing process was completed with both the bottom section and full wingsail. However, we calculated that the trim tab had enough authority to overcome some of the gravitational moment and only 1.7 lbs were necessary for use for the full wingsail. We calculated this by summing the torques due to gravity and wind. The detailed math is in Appendix E. A shroud was also designed to make the counterweight more aerodynamic and a truss was designed to support the forward plank supporting the counterweight (and the wind sensor).

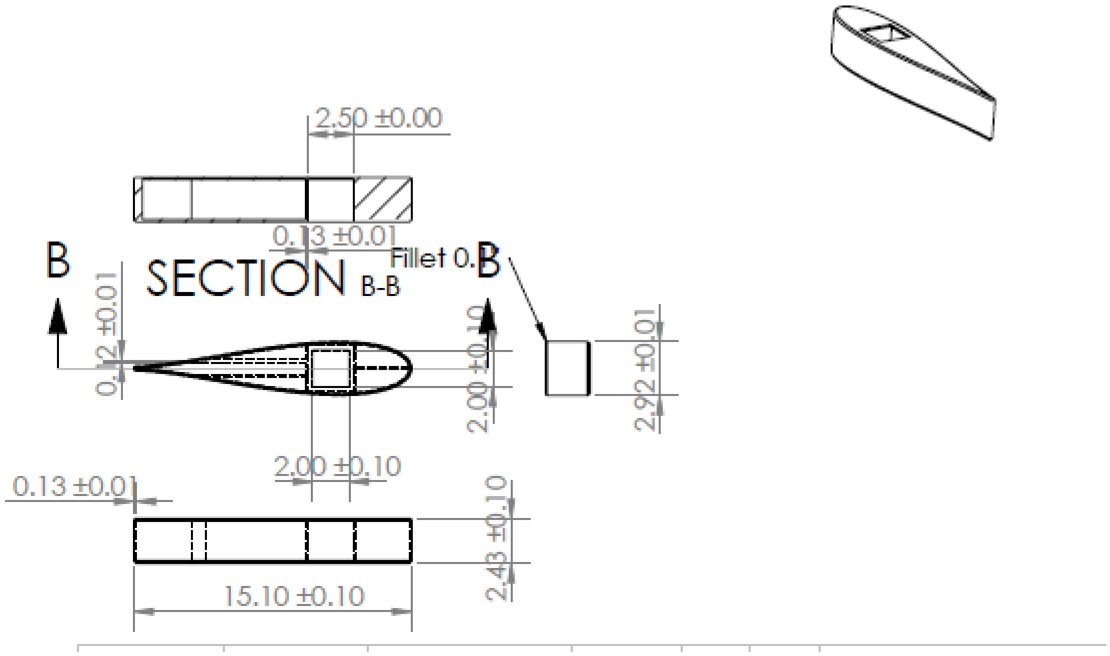


Figure 45: Design of Shroud

The counterweight consists of a series of ¼” x 2” x 2” steel plates that are bolted to the plank. Any user can add or subtract counterweight by simply adding or removing steel plates. The shroud is a 3D printed hollowed out airfoil that reduces the aerodynamic drag of the system. The truss is also 3D printed.

Figure 46: Truss

Figure 47: Shroud

Drainage System

To ensure the wingsail can be drained in such cases where the wingsail capsizes, two drainage ports were implemented. The first is located at the top of the top section of the main sail, the second being located at the bottom of the bottom section of the main sail. The drainage system consists of a male threaded piece placed through one of the pre-existing airfoils holes. A cap with internal female threads covers the exterior, and allows for the port to be opened and closed when needed. A ring located in the main sail internally prevents leaking. To drain the wingsail, it is recommended that the wingsail be separated into its two halves and drained individually.

Figure 48: Installed Drainage System

Main Joint

The main joint was 3D printed in four separate pieces. It could not be printed in one solid piece because of the size of the part and limitations of the 3D printer available on campus. The four pieces were created and then epoxied together. Once this was completed, the joint itself was attached to the mast via two airfoils attached using epoxy on both flat faces of the joint.

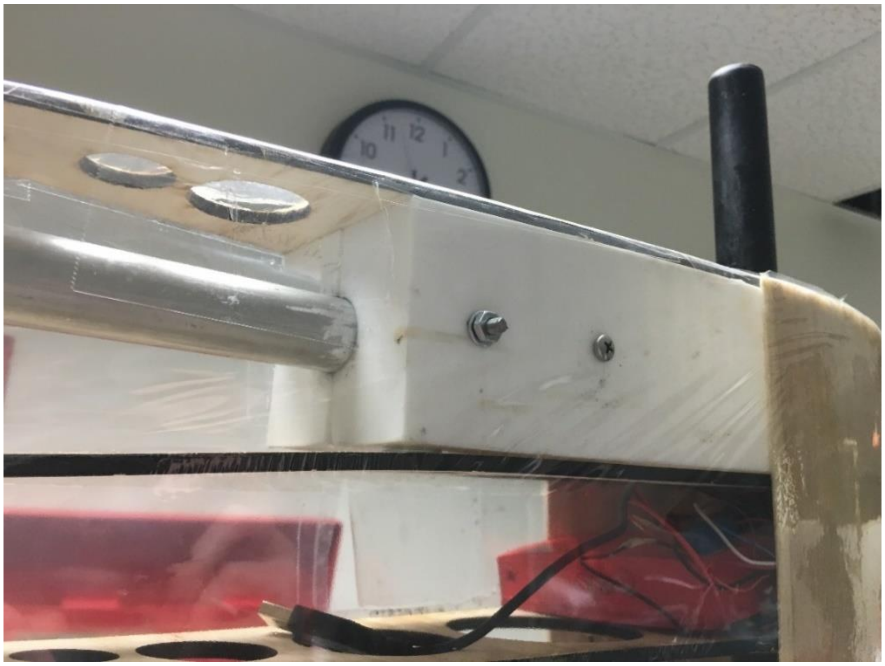


Figure 49: Main Joint

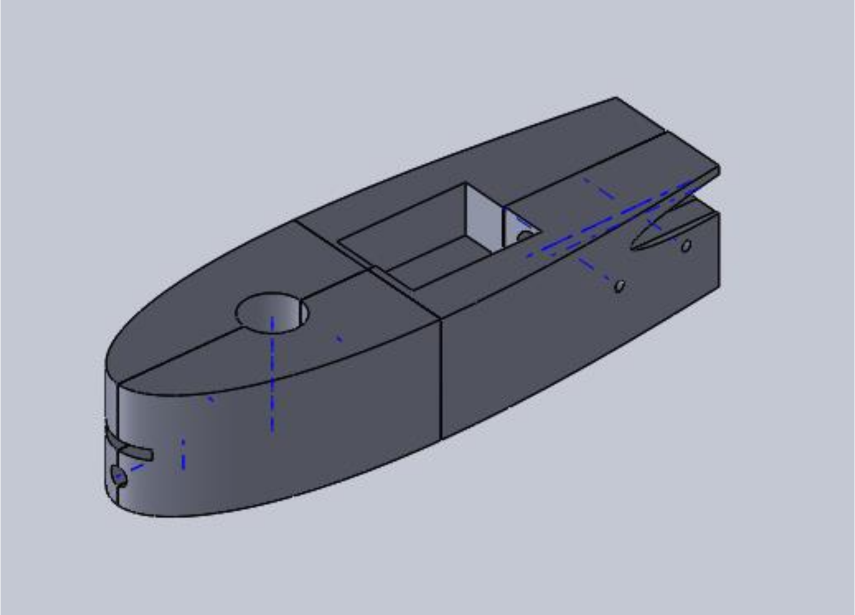


Figure 50: Main Joint Complete

Validation and Analysis of Full Scale Wingsail

Following construction of the full scale wingsail, we completed testing to validate whether the project goals set were met. We conducted three formal tests with the final prototype: a lift/drag test, a torque test, and test of the autonomous trim tab. We also determined the best method for transportation and overall system weight.

Lift and Drag Test

The lift and drag test was conducted by placing the wingsail in a stand that was made of 2x4s that also prevented rotation and translation of the mast in all planes. Two strain gauges were then placed on the mast right below the bottom of the wingsail: the first one was in line with the chord of the main sail, the other strain gauge was 90˚ to the first one. We then calibrated the strain gauges by using a spring scale. We applied a known force, and thus a known torque, on the wingsail. Three data points were taken and then plotted in Excel. A linear trend line was fitted to the points and an equation was generated by Excel to calculate the torque, and by extension the lift/drag, the wingsail generated.

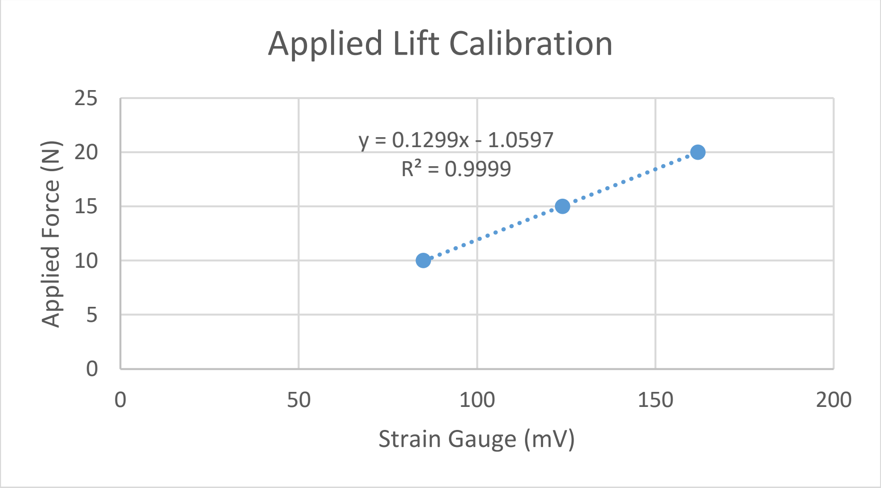


Figure 51: Lift Calibration Graphed

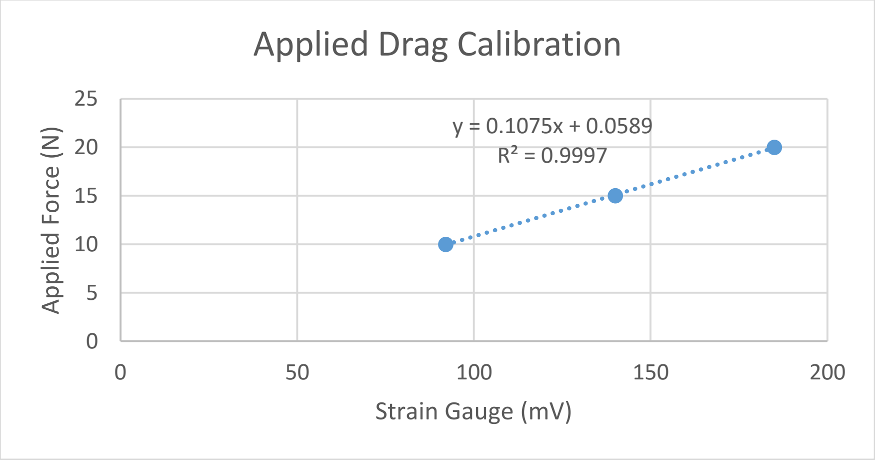


Figure 52: Drag Calibration Graphed

We then turned the stand such that the wind sensor read an angle of attack of 10+/- 4˚and used an anemometer to record wind speed. The signals from the strain gauges were run through an amplifier and then a voltmeter was used to read the voltage. When the measured angle of attack was 10+/-4˚ (measured by the wind sensor), the voltage and wind speed were recorded in an Excel sheet that automatically calculated the lift and drag from the strain gauge readings.

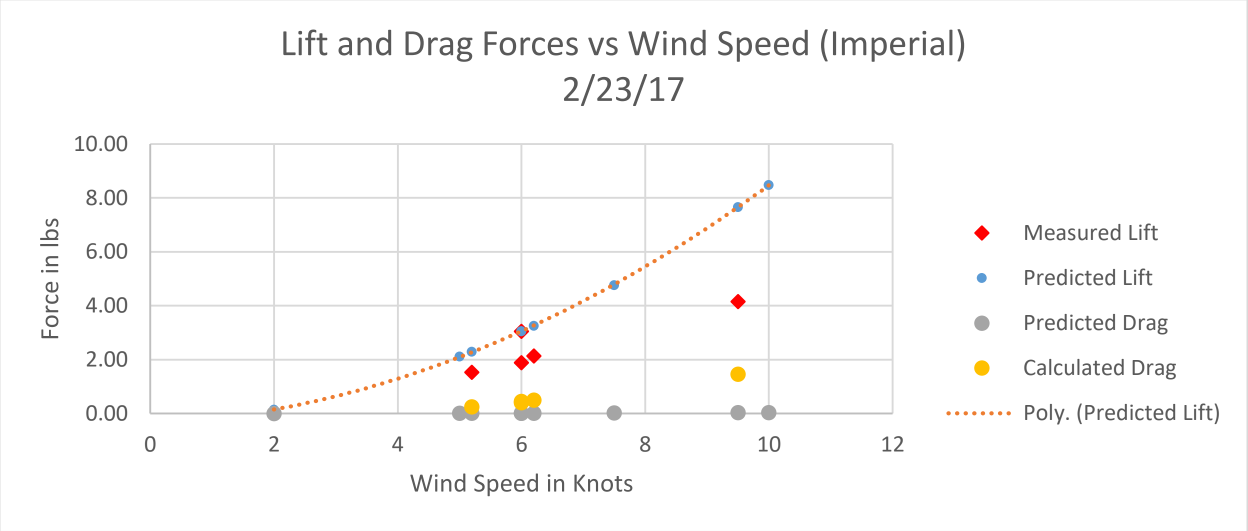


Figure 53: Lift and Drag Data Graphed

As seen in the above graph, our measured lift was lower than predicted. However, the trend of the data followed the theoretical curve and the percent error was approximately 30-40%. We were satisfied with this data as it follows a pattern and is within 40% error. Testing conditions were not ideal, as the wind speed and strain gauge voltage were being visually determined from hand held instruments. Thus, human error with respect to timing was a source of error. Moreover, the outdoor wind speed and direction were not constant and shifted frequently. A wind tunnel would have been ideal, but these resources were not feasible due to cost and time constraints.

Our measured drag data was an order of magnitude higher that what was predicted. We attributed this to the inability to properly calibrate the amplifier. The amplifier required calibration every test and in zero wind conditions. When testing outdoors, we believe there still may have been forces acting on the wingsail that did not allow the amplifiers to be properly zeroed. We considered the readings from the anemometer to be negligible, but for drag they were not. The low values of drag required precise zeroing, versus the high lift forces where more tolerance could be implemented. From this experiment, we determined the wingsail did indeed produce adequate forces to propel the vessel.

For detailed equations and data see the Appendices D and E.

Torque Test

We also determined how much torque it took to rotate the wingsail, with the goal to minimize this value. We calculated this by fitting the top bushing into the stand used for the lift/drag test and then used the spring scale to measure how much force it took to rotate the wingsail. We attached the spring scale to the trim tab rod and then measured how long the moment arm was, i.e. the distance from the center of the main mast to where we attached the spring scale. Another spring scale was attached to the mast to simulate the force on the mast from lift and drag. We measured the necessary torque to turn the mast when different forces were placed on the main sail to simulate varying wind conditions.

Measured Torque with Bushing				
Wind Speed (Simulated)	Binding Force		Force (lbs)	Measured Torque (ft lbs)
0-2 knots	no binding force		0.225	0.25
2-12 knots	30 N	6.75 lbs	0.450	0.51
12-16 knots	40 N	9 lbs	0.788	0.89
16+ knots	50 N	11.25 lbs	0.901	1.01

Table 12: Torque Test Data

Wind speed (knots)	Tab Authority (ft lbs)	Sum of resisting moments (Worst Case) (ft lbs)	Tab torque minus resisting moments	**Gravity depends on heel angle	**minimum 10* heel for boat rocking
2	0.05	0.6	-0.51	10* heel	
4	0.50	0.7	-0.20	15* heel	% Counter Weight Used
6	1.11	1.0	0.06	35* heel	50%
8	1.98	1.5	0.44	35* heel	50%
10	3.10	3.6	-0.47	35* heel	50%
12	4.61	3.1	1.47	35* heel	50%
14	6.02	3.6	2.40	35* heel	50%
16	7.94	4.2	3.76	35* heel	50%
18	10.04	4.8	5.23	35* heel	50%
20	12.40	5.5	6.89	35* heel	50%

Table 13: Comparing Torque Data

We then compared the minimum torque necessary to turn the wingsail in the bushing with the net predicted trim tab authority, which consists of how much torque the trim tab can generate minus the resisting moments of gravity, wind, and friction. As long as the trim tab generates more torque than the sum of the resisting moments, the wingsail will be able to rotate to the desired positions.

Presented above in Table 13, there are a few instances where the resisting torque is greater than the trim tab authority; however, these instances are at very low wind speeds and with only 50% of the counterweight. The SailBot MQP can verify our values with tests conducted on the water and adjust the counterweight as necessary.

Weighing Wingsail Components

The maximum allowable weight of the wingsail was set to 20lbs and was determined in collaboration with the SailBot team based upon the counterweight provided by the keel and ballast system. The wingsail's final weight is 10.2lbs; all components were measured via calibrated scale.

Weight of Wingsail Components (Lbs)				
Top Section	Bottom Section	Trim Tab Rod	Trim Tab	Counterweight
3.4	4.0	0.3	0.8	1.7
				Total Weight: 10.2

Table 14: Weights of Wingsail Components

Transportation of Wingsail

For a single individual to transport the wingsail through a building, or given area, the most cautious method is for the individual to place a hand on either side of the leading edge of the main sail where an airfoil is located. The individual should be able to firmly grasp the main sail in this manner. A support structure was also created for standing the wingsail when it is not in use. If the support structure is not available the bottom section of the main sail can be hung between two tables via the mast. The top section of the main sail can also be hung in a similar manner. Rods must be placed in the mast of the top section of the wingsail to be hung. To ensure the security of the wingsail, the rods must be at least 12" long and 6" of the rod must be located within the mast. The image below demonstrates proper carrying techniques for the wingsail.

For vehicular transport, the main sail should be broken into two halves and stacked on top of each other. The halves should be laid such that the trailing edge of the top section of the main sail is placed on the leading edge of the bottom section of the main sail. The trim tab can be stacked on top of the two main sail halves. To ensure that the wingsail is not damaged or pierced during transportation, foam should be placed around the wingsail.

Figure 54: Proper Carrying of Sail

Social Implications

The wingsail provides a low social impact due to its minimal interaction with humans and self-contained nature. There are still however implications that should be noted. Under high wind conditions the wingsail will generate high forces. When being carried or transported the user should be careful, keep the wingsail low, and hold it with a firm grasp to avoid the wingsail becoming free and possibly dangerous to those around it. When the wingsail is in the boat it is adequately contained; however, when the wind velocity increases, there is the possibility that the rotation of the wingsail can be quick enough for the trim tab and the trim tab rod to swing and cause injury.

When adding LEDs to the wingsail we originally considered using red and green LEDs to signal state and direction of the wingsail, however this could interfere with the standard red and green to signal port and starboard on nautical vessels. We refrained from this combination of lights to avoid possible confusion.

The wingsail generally does not have sharp edges due to its elegant curves. However, in a few locations there were possible sharp edges. The ends of the carbon fiber rod on the trailing edges were epoxied flush with the ribs to avoid any sharp overhang. The aluminum plank was rounded in the front to smooth out the corners. We considered the harmful nature of such edges during the construction process, and evaded them accordingly.

While constructing the wingsail we also needed to ensure our personal safety. Products used during the construction of the wingsail are harmful and carcinogenic without the proper safety apparatuses. When laying fiberglass and resin we used gloves, long sleeves, goggles, and masks. When cutting and sanding fiberglass we also wore masks and goggles.

Recommendations and Conclusions

Conclusions

Table 15 presents the categories by which we measured our success, all goals were met except for goal 1 that will require testing on the water. This testing will be performed by the SailBot MQP. Conclusions drawn from this MQP are broken into three primary sections including conclusions drawn from analysis and preliminary design, construction techniques, and testing.

Analysis and Preliminary Design

The success of this MQP is attributed to the initial analysis and preliminary design performed. Initial analysis on the communications, airfoil shape, mast selection, necessary vessel/wingsail interface, etc., led to few sudden alterations to the design later in the MQP. As will be discussed in the *Recommendations for Future Work* section, we did find fault in our lack of analysis for the wind sensor plank. We did not account for the oscillation produced by the heave and pitch of the boat once in the water. Our solution to this problem came in the addition of a truss system, however this truss system affects the aerodynamic nature of the sail.

Construction Techniques

From the construction of the half scale model we found that the best mode to produce the wingsail was to use many of the same techniques traditionally used to build scale model airplanes. For the final model we decided to not utilize polycarbonate for two reasons. The primary problem faced was manufacturing mistakes. The polycarbonate formed well to the leading edge of the mold, however curling of the edges did occur. The curling of the edges did not allow for meshing of the polycarbonate sections. For the leading edge of the wingsail it is necessary that the surface be smooth with no seams. To attempt to remedy this issue, we made a section of a female mold to test. However, the polycarbonate still curved around the ends of the male mold with the female mold in place. The second deciding factor to not utilize the polycarbonate was weight. The polycarbonate weighs more than balsa layered with fiberglass and resin.

Testing Procedures and Results

Results from the lift and drag test of the full scale wingsail were mostly within the desired accuracy (40% error), but present areas for increased precision. Our testing was completed on the top of the Gateway garage on the WPI campus to maximize the consistency of airflow. However, we still experienced gusty wind, or sudden bursts of high velocity air. Ideally, we should have completed testing in an indoor wind tunnel, where we could have constant, known wind speeds. We ruled out testing our full scale in a wind tunnel due to cost, and the use of fans was not considered due to highly inconsistent wind speeds along the wingsail. The calibration process for the amplifier would also be simplified if the wind speed was able to be reduced to zero in a chamber.

The other test of notability is the torque test on the full scale wingsail. The test did produce favorable results in 7/10 wind speeds. We determined from the test that additional counterweight should be applied to the sail to maintain trim tab authority in low wind speeds. Additional counterweight is acceptable as the final weight of the system was 10.2lbs, far under the 20lbs maximum.

Project Objectives			
Goal Number	Goal	Success or Failure	Evidence of Success or Failure
1	The wingsail must be able to travel in both upwind and downwind conditions. Meaning when traveling upwind, the wingsail must present tacking capabilities.	Unknown	The SailBot MQP does not plan to conduct water testing until after submission of our project.
2	The wingsail must present a method to stop generating a thrust force on the wingsail.	Success	Demonstrated in outdoor testing on land. The trim tab goes minimum lift mode.
3	Overall length including hull, all spars and foils oriented in their fore and aft directions and at their maximum extensions if applicable, shall not exceed 2 meters measured parallel to the waterline.	Success	Measured Value
4	Beam shall not exceed 3-meters overall width at zero heel angle.	Success	Measured Value
5	Total overall height from the lowest underwater point to the highest point on the largest rig shall not exceed 5 meters. (Sensors and mounting not included).	Success	Measured Value
6	The wingsail must be capable of being broken up into sections that allow it to be easily transported and to accommodate for various wind velocities.	Success	Wingsail can be broken into three components: top section, bottom section, and the trim tab.
7	Sail sections must be able to be re-assembled with tools available to the SailBot team and with relative speed.	Success	SailBot has access to same tools we used to build the wingsail.
8	The wingsail must present some method of draining in cases where capsizing occurs.	Success	Drainage system installed for top and bottom sections of the airfoil covered main wing.
9	Wingsail components must be able to be reproduced at the WPI campus, or parts not self-made must be available through an alternative source.	Success	All parts were created on WPI campus, or ordered online.

Goal Number	Goal	Success or Failure	Evidence of Success or Failure
10	The wingsail must be constructed in a manner that allows for easy alteration and attachment to another hull.	Success	There is 21” of mast below the beginning of the main wing to modify the wingsail to fit another boat design.
11	The wingsail and all components related to the wingsail must be constrained to a maximum total weight of 20lbs.	Success	The total weight as defined in the *Testing and Analysis* section is 10.2 lbs.
12	The wingsail must be able to send and receive messages to the hulls processor.	Success	The wingsail wirelessly sends and receives messages with the hull’s processor.
13	The wingsail must be able to sense angle of attack and process this data along with heel angle and desired state to consistently maintain optimal forces.	Success	The angle of attack, heel angle, and state are all used to achieve the ideal forces.

Table 15: Project Objectives- Outcomes

Recommendations for Future Work

This project is considered a success, however we do have some recommendations and lessons learned if we, or another party, were to make another wingsail. First, we would recommend using a different "plank" than the one currently used to hold the counterweight and wind sensor. The current cross section is a skinny rectangle, with the long end horizontally oriented. In this configuration, the aluminum plank achieves its goal of providing a flat surface to mount the wind sensor on. However, the plank is ill suited to support the counterweight without significant bending and thus requires a truss, which disrupts the aerodynamics of the wingsail. The flexibility of the plank also raises concerns about oscillation. A square or even hexagonal aluminum or carbon fiber tube may provide a much stiffer, yet flat protrusion on with the wind sensor and counterweight can be mounted.

We also recommend that the counterweight be moved to the bottom of the wingsail to increase the stability of the boat by lowering its center of gravity. An additional joint, similar to the main joint, would need to be created and installed above the lowermost airfoil to support the plank. While this would incur additional cost and weight, we believe these penalties would be offset by the increase in stability. Any future builders would also have to ensure that lowering the counterweight would not generate too much of a twisting moment between the tab and the counterweight when the boat heels. We believe this problem to be solvable, but it will require attention to ensure a rib does not break under the additional load.

Appendix A- Engineering Drawings

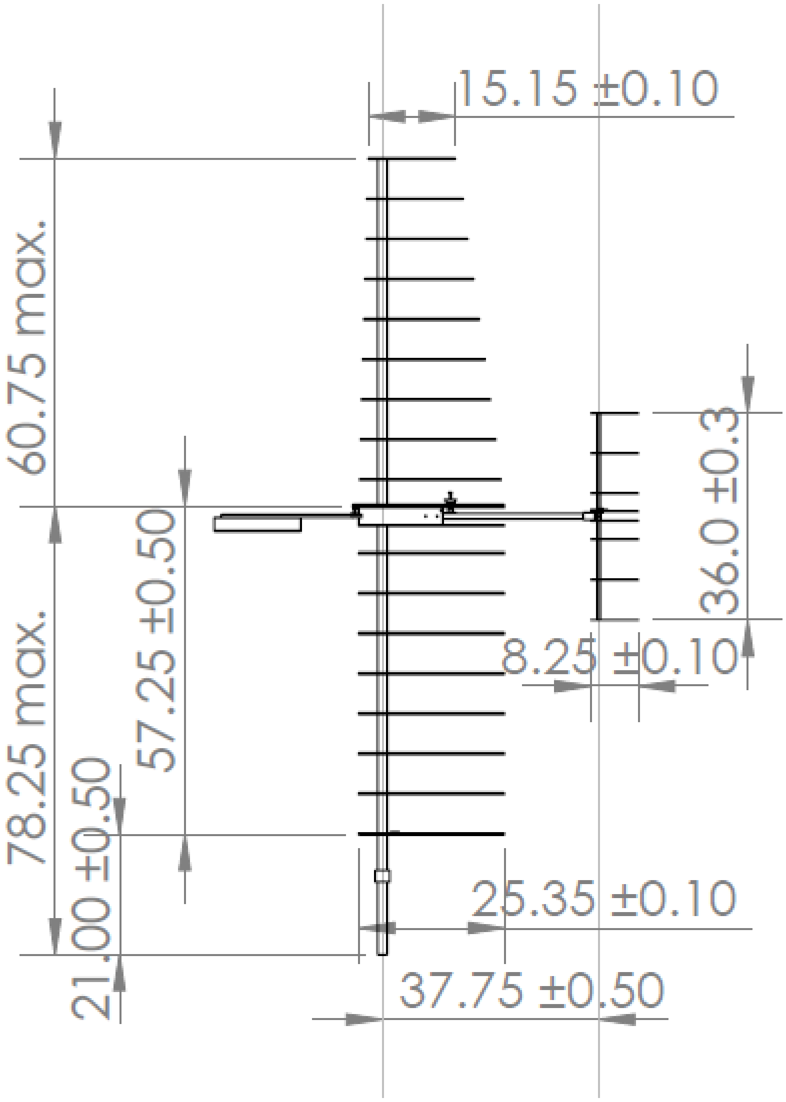


Figure 55: Complete Wingsail Dimensions

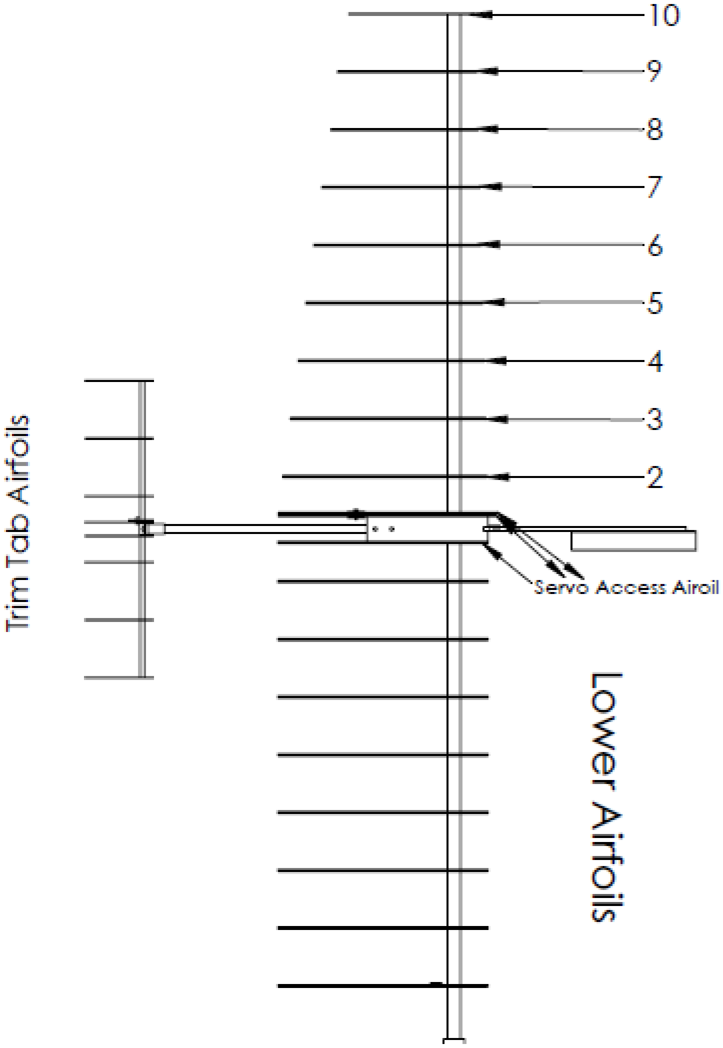


Figure 56: Airfoil Numbering

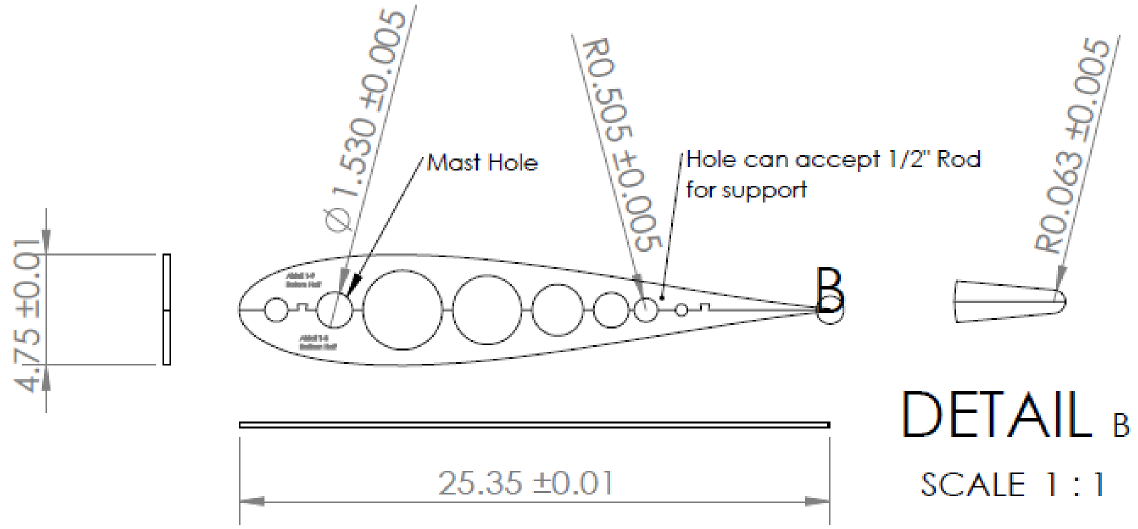


Figure 57: Lower Airfoil Design

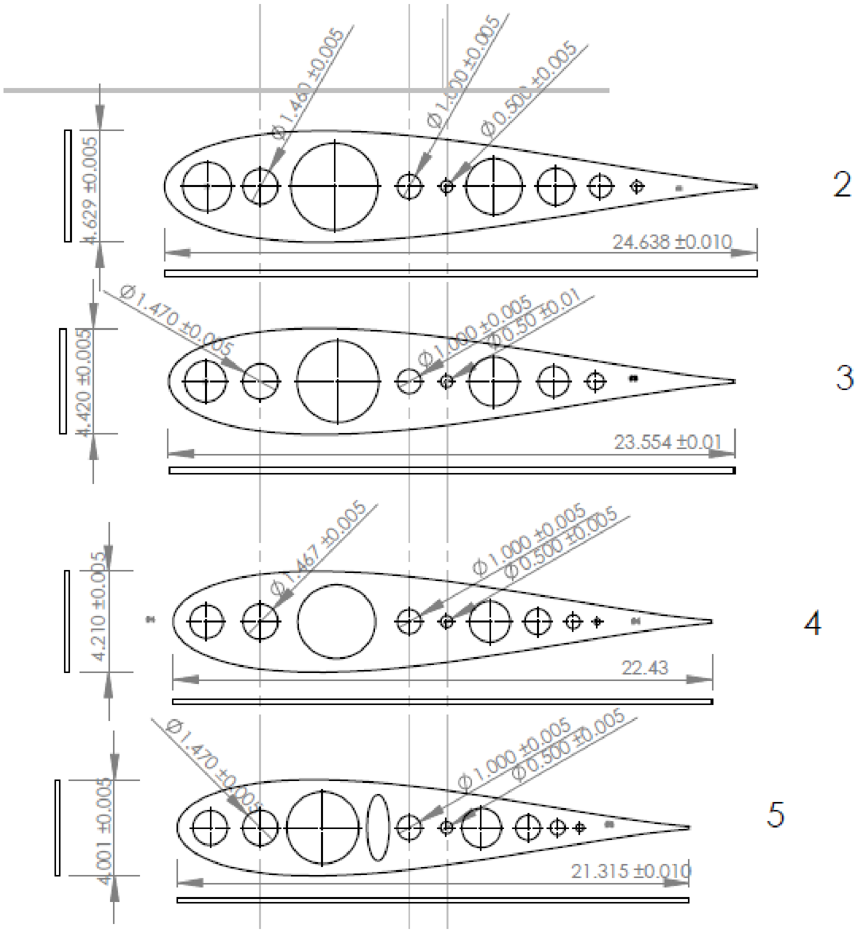


Figure 58: Tapered Airfoils 2-5

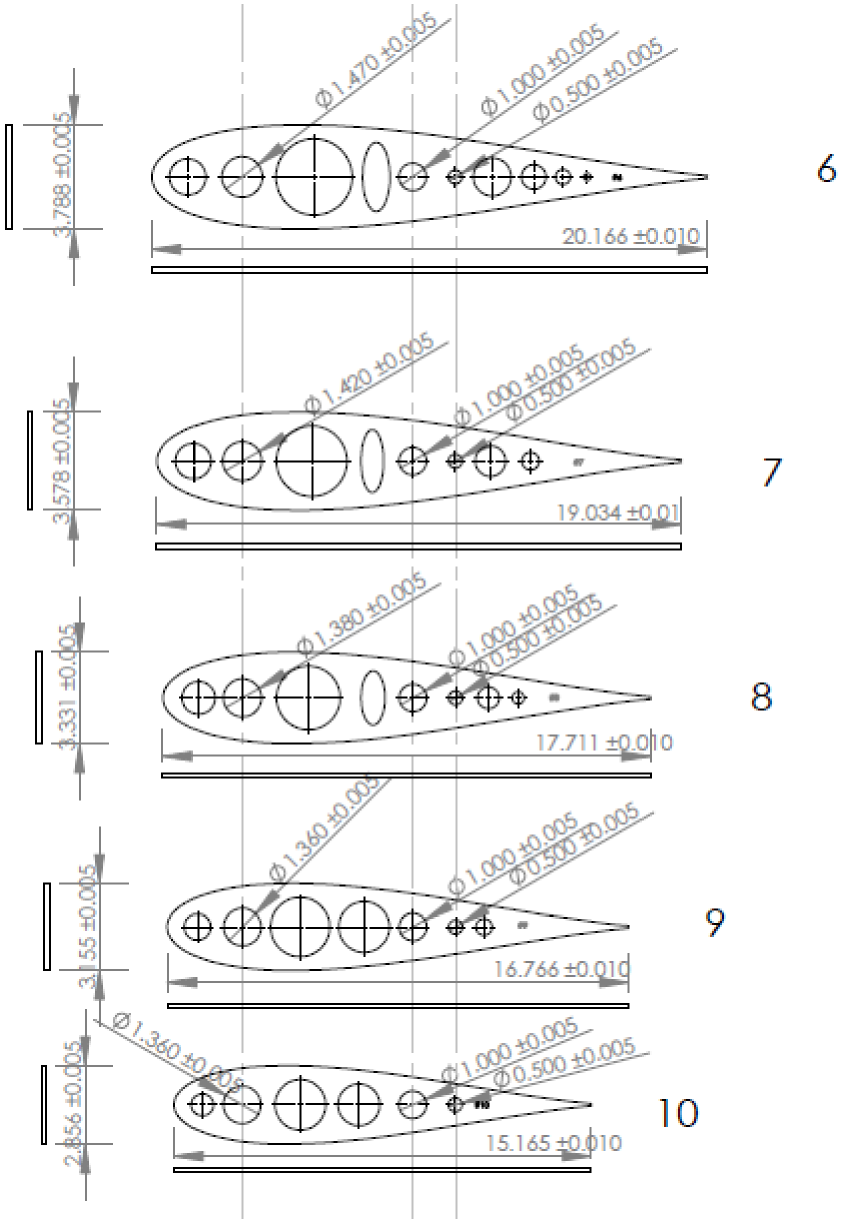


Figure 59: Tapered Airfoils 6-10

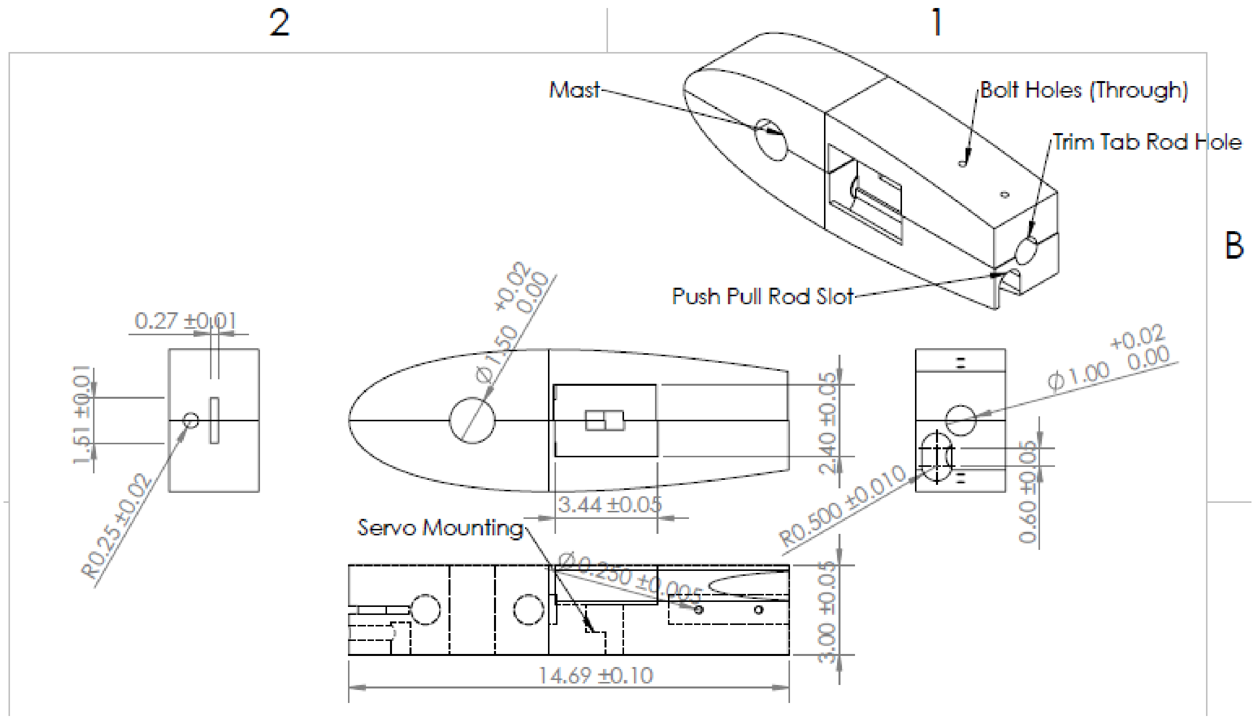


Figure 60: Main Joint Dimensions

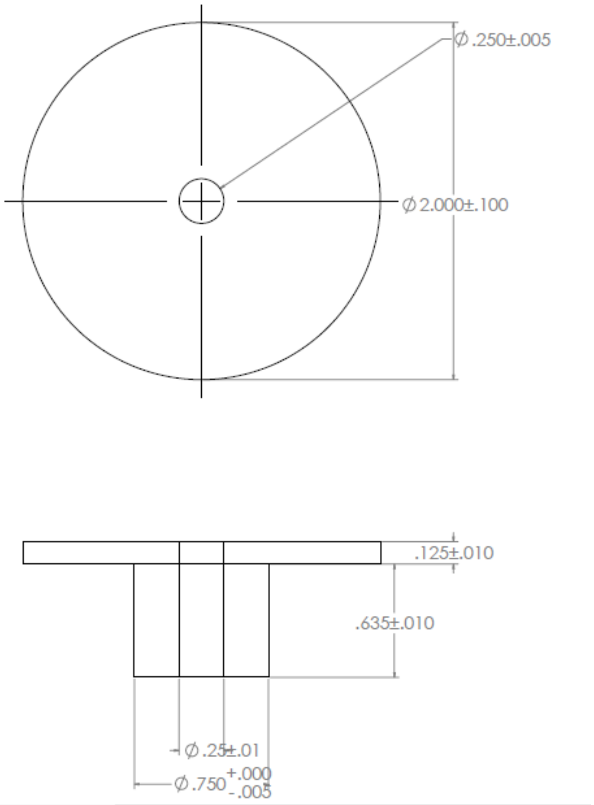


Figure 61: Half 1 of Button

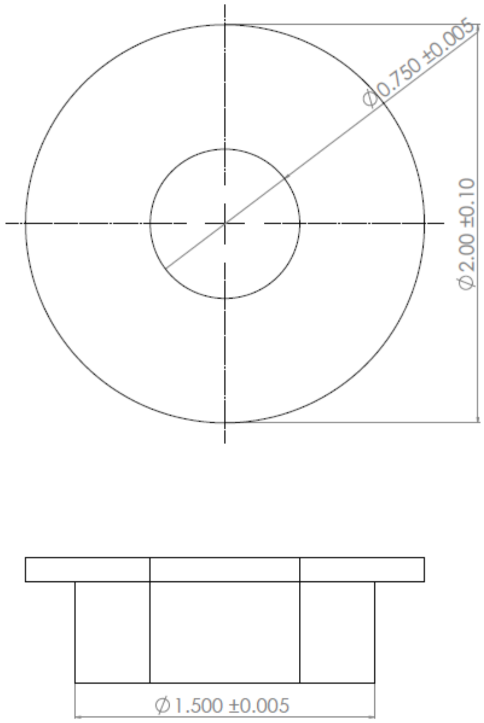


Figure 62: Half 2 of Button

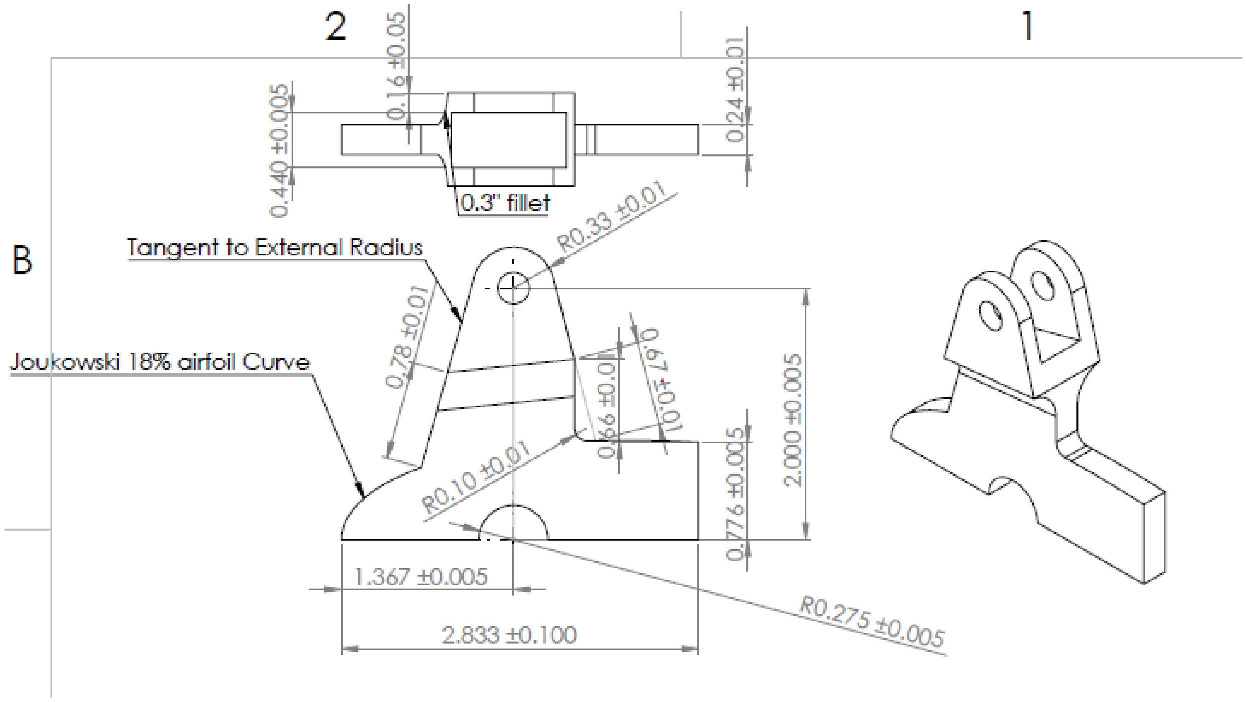


Figure 63: Tab Servo Connector Part 1

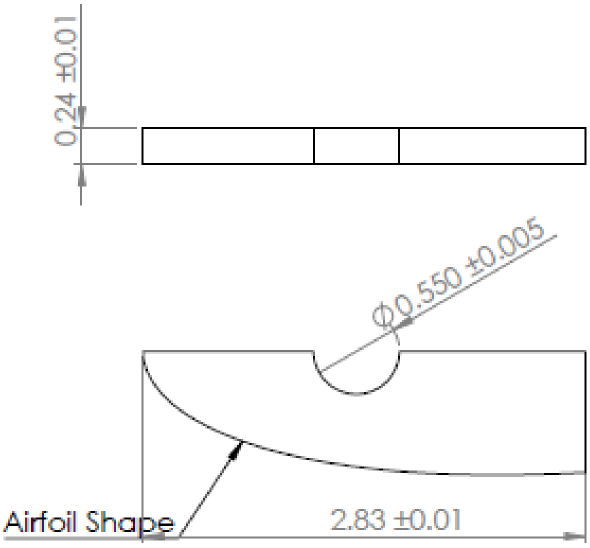


Figure 64: Tab Rod Connector Part 2

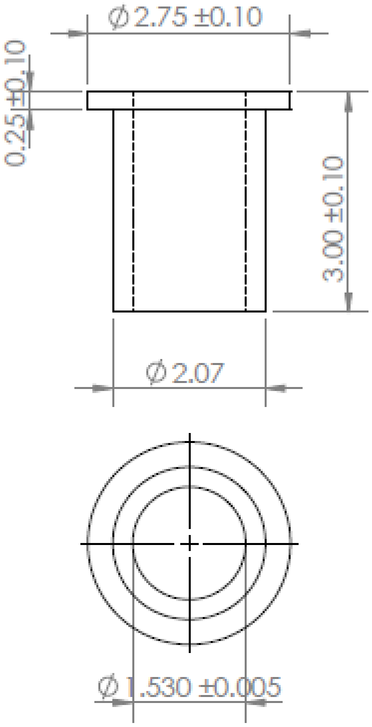


Figure 65: Bushing

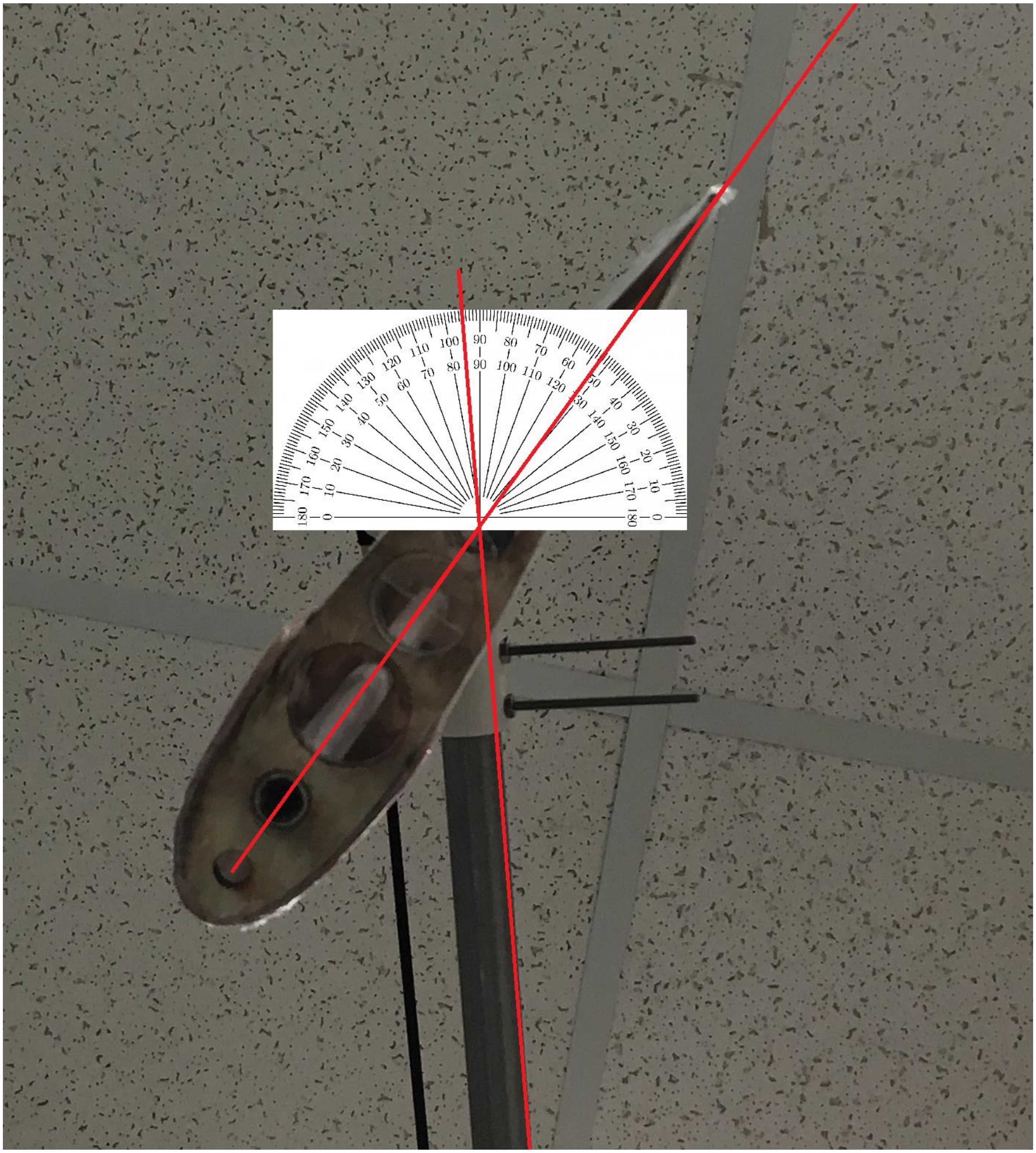


Figure 66: Maximum Actuation Trim Tab

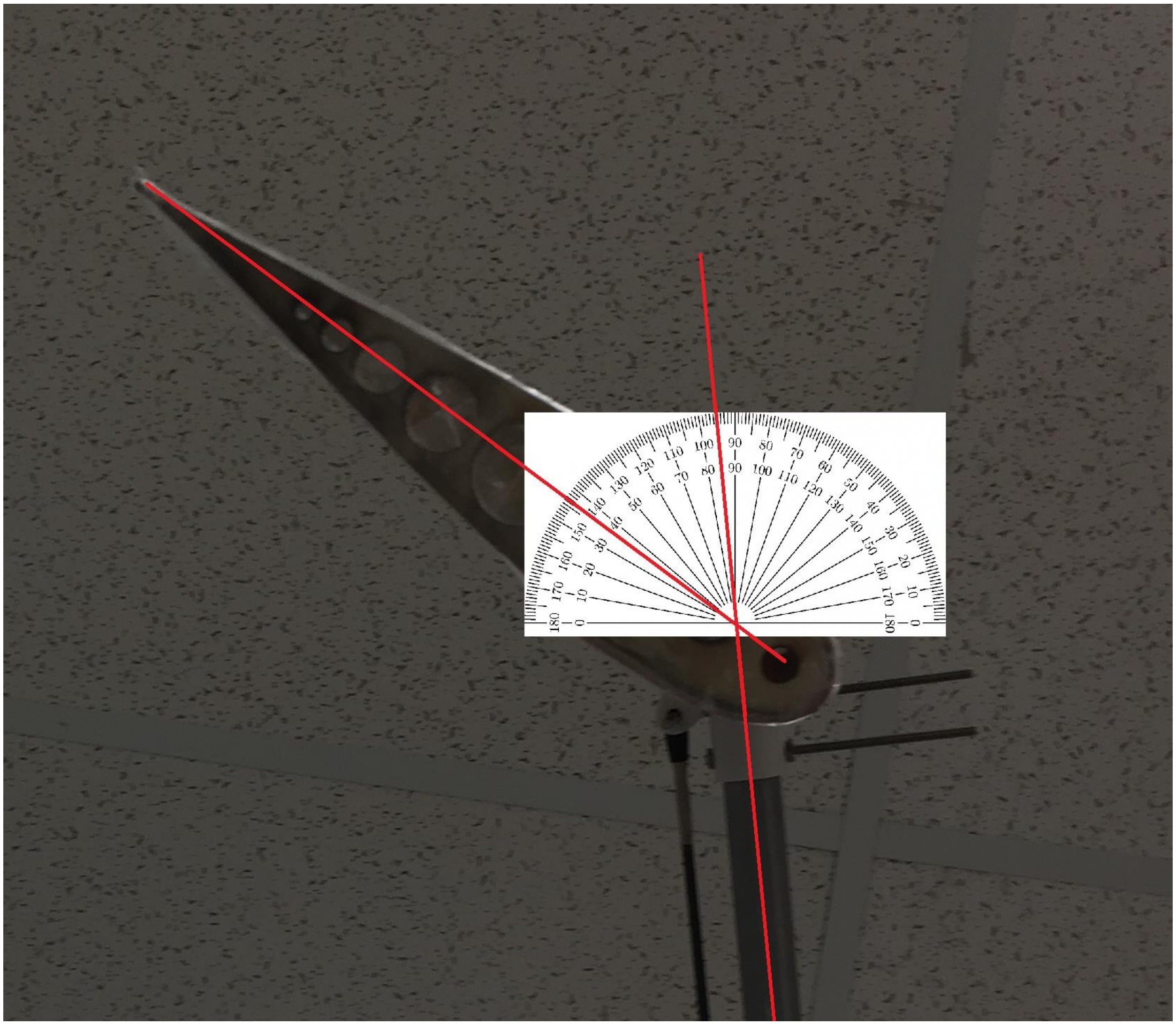
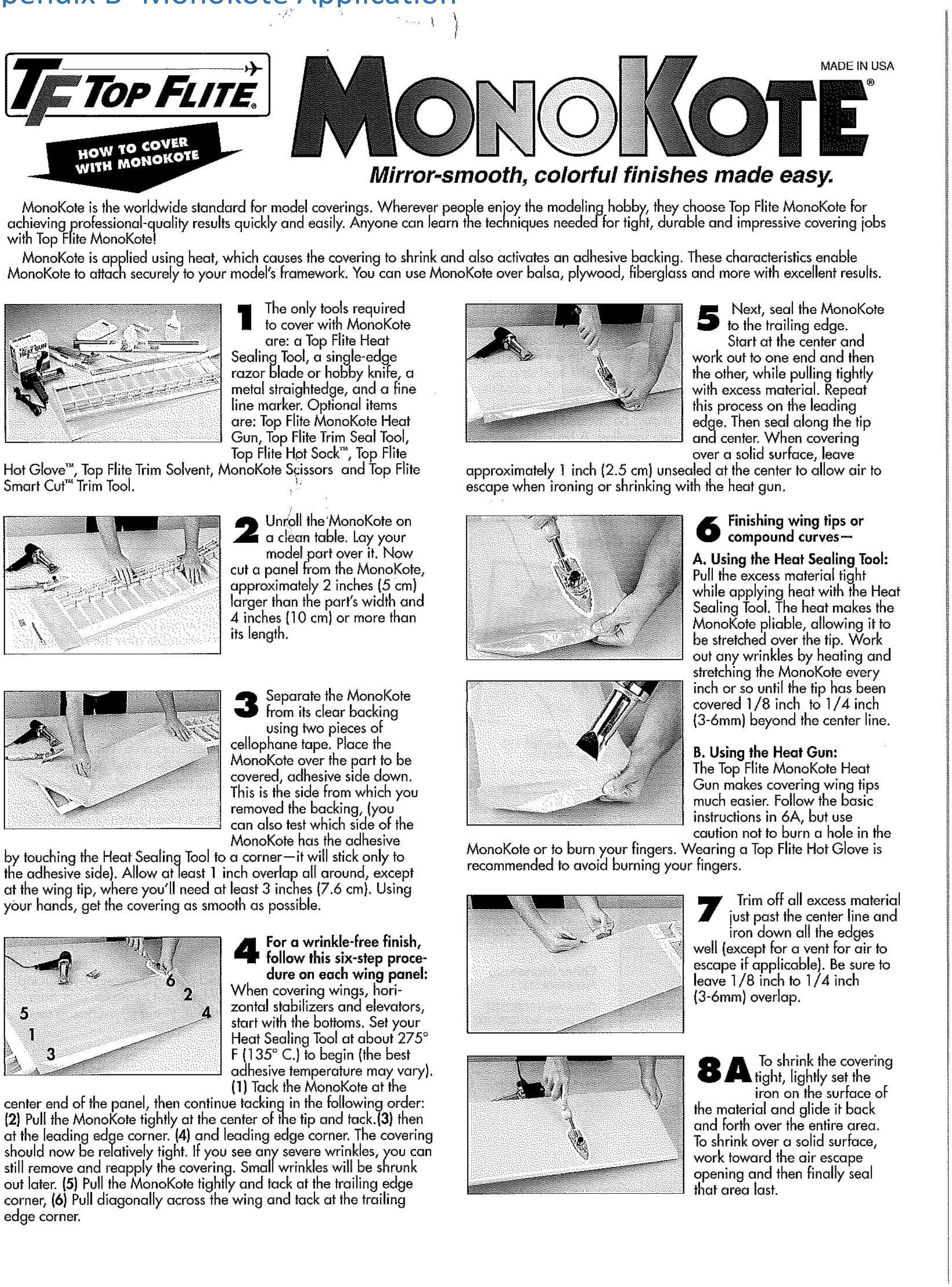


Figure 67: Maximum Actuation Trim Tab

Appendix B- Monokote Application



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HOW TO COVER WITH MONOKOTE

MONOKOTE®

MADE IN USA

Mirror-smooth, colorful finishes made easy.

MonoKote is the worldwide standard for model coverings. Wherever people enjoy the modeling hobby, they choose Top Flite MonoKote for achieving professional-quality results quickly and easily. Anyone can learn the techniques needed for tight, durable and impressive covering jobs with Top Flite MonoKote!

MonoKote is applied using heat, which causes the covering to shrink and also activates an adhesive backing. These characteristics enable MonoKote to attach securely to your model's framework. You can use MonoKote over balsa, plywood, fiberglass and more with excellent results.

1 The only tools required to cover with MonoKote are: a Top Flite Heat Sealing Tool, a single-edge razor blade or hobby knife, a metal straightedge, and a fine line marker. Optional items are: Top Flite MonoKote Heat Gun, Top Flite Trim Seal Tool, Top Flite Hot Sock™, Top Flite Hot Glove™, Top Flite Trim Solvent, MonoKote Scissors and Top Flite Smart Cut™ Trim Tool.

2 Unroll the MonoKote on a clean table. Lay your model part over it. Now cut a panel from the MonoKote, approximately 2 inches (5 cm) larger than the part's width and 4 inches (10 cm) or more than its length.

3 Separate the MonoKote from its clear backing using two pieces of cellophane tape. Place the MonoKote over the part to be covered, adhesive side down. This is the side from which you removed the backing, (you can also test which side of the MonoKote has the adhesive by touching the Heat Sealing Tool to a corner—it will stick only to the adhesive side). Allow at least 1 inch overlap all around, except at the wing tip, where you'll need at least 3 inches (7.6 cm). Using your hands, get the covering as smooth as possible.

4 **For a wrinkle-free finish, follow this six-step procedure on each wing panel:** When covering wings, horizontal stabilizers and elevators, start with the bottoms. Set your Heat Sealing Tool at about 275° F (135° C.) to begin (the best adhesive temperature may vary). **(1)** Tack the MonoKote at the center end of the panel, then continue tacking in the following order: **(2)** Pull the MonoKote tightly at the center of the tip and tack.**(3)** then at the leading edge corner. **(4)** and leading edge corner. The covering should now be relatively tight. If you see any severe wrinkles, you can still remove and reapply the covering. Small wrinkles will be shrunk out later. **(5)** Pull the MonoKote tightly and tack at the trailing edge corner, **(6)** Pull diagonally across the wing and tack at the trailing edge corner.

5 Next, seal the MonoKote to the trailing edge. Start at the center and work out to one end and then the other, while pulling tightly with excess material. Repeat this process on the leading edge. Then seal along the tip and center. When covering over a solid surface, leave approximately 1 inch (2.5 cm) unsealed at the center to allow air to escape when ironing or shrinking with the heat gun.

6 **Finishing wing tips or compound curves—**

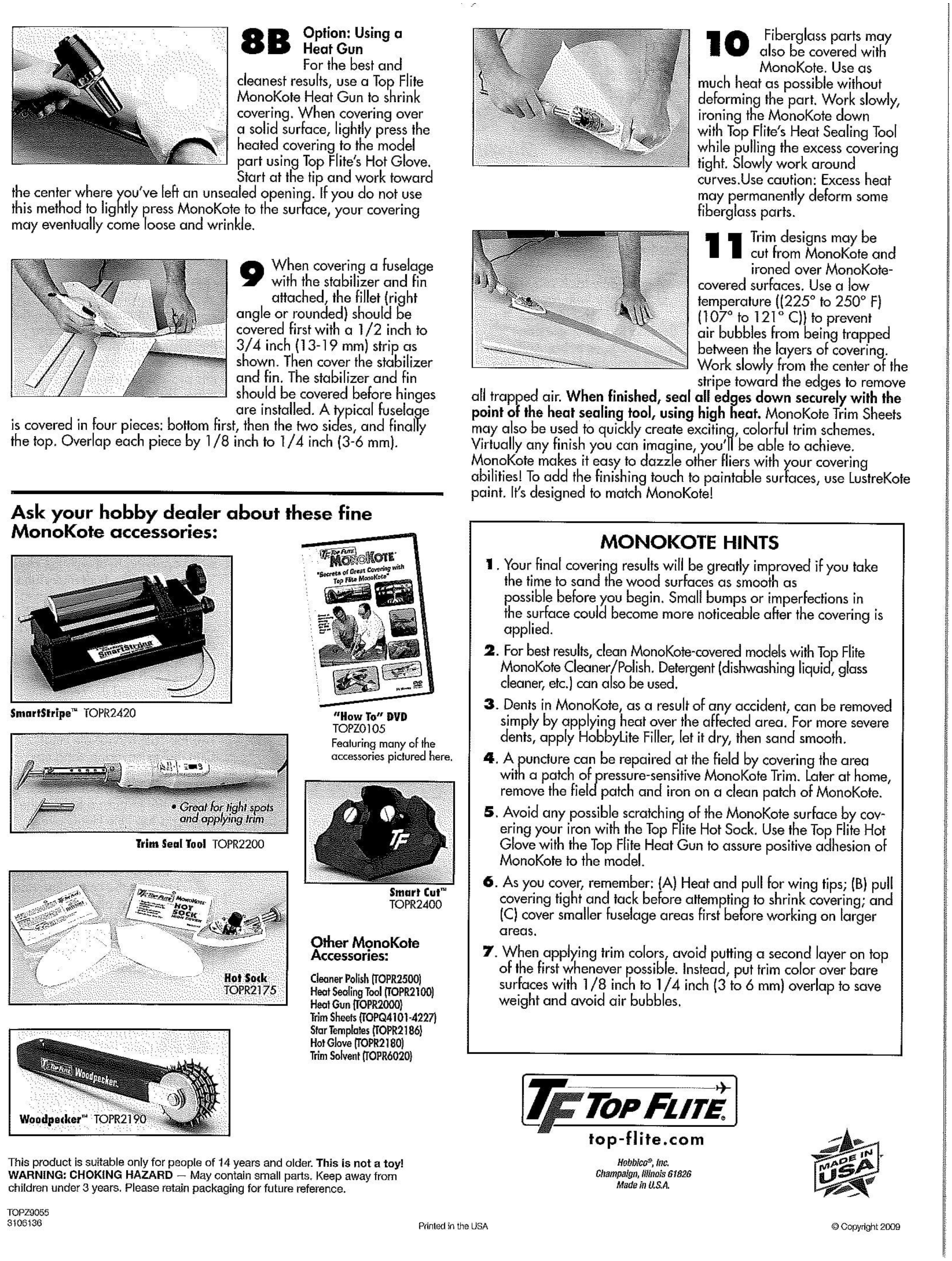
A. Using the Heat Sealing Tool: Pull the excess material tight while applying heat with the Heat Sealing Tool. The heat makes the MonoKote pliable, allowing it to be stretched over the tip. Work out any wrinkles by heating and stretching the MonoKote every inch or so until the tip has been covered 1/8 inch to 1/4 inch (3-6mm) beyond the center line.

B. Using the Heat Gun: The Top Flite MonoKote Heat Gun makes covering wing tips much easier. Follow the basic instructions in 6A, but use caution not to burn a hole in the MonoKote or to burn your fingers. Wearing a Top Flite Hot Glove is recommended to avoid burning your fingers.

7 Trim off all excess material just past the center line and iron down all the edges well (except for a vent for air to escape if applicable). Be sure to leave 1/8 inch to 1/4 inch (3-6mm) overlap.

8A To shrink the covering tight, lightly set the iron on the surface of the material and glide it back and forth over the entire area. To shrink over a solid surface, work toward the air escape opening and then finally seal that area last.

Figure 68: Monokote Instructions part 1



8B **Option: Using a Heat Gun**

For the best and cleanest results, use a Top Flite MonoKote Heat Gun to shrink covering. When covering over a solid surface, lightly press the heated covering to the model part using Top Flite's Hot Glove. Start at the tip and work toward the center where you've left an unsealed opening. If you do not use this method to lightly press MonoKote to the surface, your covering may eventually come loose and wrinkle.

9 When covering a fuselage with the stabilizer and fin attached, the fillet (right angle or rounded) should be covered first with a 1/2 inch to 3/4 inch (13-19 mm) strip as shown. Then cover the stabilizer and fin. The stabilizer and fin should be covered before hinges are installed. A typical fuselage is covered in four pieces: bottom first, then the two sides, and finally the top. Overlap each piece by 1/8 inch to 1/4 inch (3-6 mm).

Ask your hobby dealer about these fine MonoKote accessories:

SmartStripe™ TOPR2420

"How To" DVD
TOPZ0105
Featuring many of the accessories pictured here.

• *Great for tight spots and applying trim*

Trim Seal Tool TOPR2200

Smart Cut™
TOPR2400

Hot Sock
TOPR2175

Other MonoKote Accessories:

Cleaner Polish (TOPR2500)
Heat Sealing Tool (TOPR2100)
Heat Gun (TOPR2000)
Trim Sheets (TOPQ4101-4227)
Star Templates (TOPR2186)
Hot Glove (TOPR2180)
Trim Solvent (TOPR6020)

Woodpecker™ TOPR2190

10 Fiberglass parts may also be covered with MonoKote. Use as much heat as possible without deforming the part. Work slowly, ironing the MonoKote down with Top Flite's Heat Sealing Tool while pulling the excess covering tight. Slowly work around curves.Use caution: Excess heat may permanently deform some fiberglass parts.

11 Trim designs may be cut from MonoKote and ironed over MonoKote-covered surfaces. Use a low temperature ((225° to 250° F) (107° to 121° C)) to prevent air bubbles from being trapped between the layers of covering. Work slowly from the center of the stripe toward the edges to remove all trapped air. **When finished, seal all edges down securely with the point of the heat sealing tool, using high heat.** MonoKote Trim Sheets may also be used to quickly create exciting, colorful trim schemes. Virtually any finish you can imagine, you'll be able to achieve. MonoKote makes it easy to dazzle other fliers with your covering abilities! To add the finishing touch to paintable surfaces, use LustreKote paint. It's designed to match MonoKote!

MONOKOTE HINTS

1. Your final covering results will be greatly improved if you take the time to sand the wood surfaces as smooth as possible before you begin. Small bumps or imperfections in the surface could become more noticeable after the covering is applied.
2. For best results, clean MonoKote-covered models with Top Flite MonoKote Cleaner/Polish. Detergent (dishwashing liquid, glass cleaner, etc.) can also be used.
3. Dents in MonoKote, as a result of any accident, can be removed simply by applying heat over the affected area. For more severe dents, apply HobbyLite Filler, let it dry, then sand smooth.
4. A puncture can be repaired at the field by covering the area with a patch of pressure-sensitive MonoKote Trim. Later at home, remove the field patch and iron on a clean patch of MonoKote.
5. Avoid any possible scratching of the MonoKote surface by covering your iron with the Top Flite Hot Sock. Use the Top Flite Hot Glove with the Top Flite Heat Gun to assure positive adhesion of MonoKote to the model.
6. As you cover, remember: (A) Heat and pull for wing tips; (B) pull covering tight and tack before attempting to shrink covering; and (C) cover smaller fuselage areas first before working on larger areas.
7. When applying trim colors, avoid putting a second layer on top of the first whenever possible. Instead, put trim color over bare surfaces with 1/8 inch to 1/4 inch (3 to 6 mm) overlap to save weight and avoid air bubbles.

This product is suitable only for people of 14 years and older. **This is not a toy!**
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Figure 69: Monokote Instructions part 2

Appendix C- Mast Deflection

Figure 70: Deflection Curve for Mast

Appendix D- Testing Data

Table 16: Strain Gauge Calibration

Strain Gauge Calibration						
Applied Lift				Applied Drag		
Applied Load (N)	Lift Gauge (mV)	Drag Gauge (mV)		Applied Load (N)	Lift Gauge (mV)	Drag Gauge (mV)
10	85	6		10	8	92
15	124	10.2		15	14	140
20	162	15		20	20	185

The equations generated from the calibration are as follows:

$\text{Lift}_{\text{force}}(\text{N}) = 0.1299*\text{signal (mV)} - 1.0597$ R = 0.9999

$\text{Drag}_{\text{force}}(\text{N}) = 0.1075*\text{signal (mV)} + 0.0589$ R = 0.9997

Table 17: Lift and Drag Raw Data

Test Results 2/23/2017								
Wind	Lift Gauge (mV)	Drag Gauge (mv)	Calcualted Lift (N)	Predicted Lift (N)	Lift % Error	Calculated Drag (N)	Predicted Drag (N)	Drag % Error
6	119	18	13.57	13.55	0%	1.9939	0.06	3223%
5.2	64	10	6.81	10.18	-33%	1.1339	0.05	2168%
6	77	16	8.40	13.55	-38%	1.7789	0.06	2865%
9.5	159	60	18.48	34	-46%	6.5089	0.15	4239%
6.2	86	20	9.51	14.47	-34%	2.2089	0.07	3056%
2				0.63			0	
5				9.41			0.04	
7.5				21.17			0.1	
10				37.63			0.17	
			Calculated Lift (lbs	Predicted Lift (lbs)		Calculated Drag (lbs)	Calculated Drag (lbs)	
6			3.06	3.05		0.45	0.01	
5.2			1.53	2.29		0.26	0.01	
6			1.89	3.05		0.40	0.01	
9.5			4.16	7.66		1.47	0.03	
6.2			2.14	3.26		0.50	0.02	
				0.00			0.00	
				0.00			0.00	
2				0.14			0.00	
5				2.12			0.01	
7.5				4.77			0.02	
10				8.48			0.04	

Appendix E- Mathematical Equations

Excel Simulation Equations

$$L = \frac{C_L \; A \; p \, v^2}{2}$$

L = Lift (Force)
C_L= Lift Coefficient
ρ = Air Density
v = Apparent Wind Speed
A = Planform Area

2

D = Drag (Force)
C_L= Lift Coefficient
ρ = Air Density
v = Apparent Wind Speed
A = Planform Area

$$A = \sqrt{Bx^2 + (Ty + By)^2}$$

A = Apparent Wind Speed Magnitude
T= True Wind
θ_B = Angle Between Boat and True Wind
B_x= Boat Wind in x direction = Bsin(θ_B)
B_y= Boat Wind in y direction = Bsin(θ_B)
B = Boat Speed

$$A_x = Bx$$

$$Ay = T + By$$

$$\Theta_A = \pi + tan(\frac{|A_x|}{|A_Y|})$$

$$\Theta_L = \Theta_A - \frac{\pi}{2}$$

= Lift Direction Relative True Wind

= Lift Direction Relative True Wind

$$\Theta_H = \Theta_L - \Theta_B$$

$$T_F = L\ cos(\Theta_H)$$ = Thrust Force

$$H_F = L\ sin(\Theta_H)$$ = Heeling Force

$$M_H = H_f * \frac{h}{2}$$ = Heeling Moment

h = mast height

$$M_R = W_B * l$$ = Righting Moment

W_B = Weight Ballast
l = height of ballast

Heeling Angle is the angle of heel when $M_H = M_R$ and is found iteratively using Excel

Torque Calculations for Servo

(Max Lift)*(Mast – 1/4 chord of main sail) = (X)*(Mast-tab distance)

X = minimum force tab must generate

(X)(1/4 chord of tab) = minimum required servo torque

Moment Calculations around Mast

Trim Tab Authority (torque) = (Lift from Trim Tab)*(Distance from Mast to Trim Tab)

Moment around Main Mast from Gravity = (Weight of Trim Tab)*(Distance from Mast to Trim Tab)*sin(Heel Angle)

Moment from Mainsail around Main Mast = (Lift from Main Sail)*(Distance from ¼ Chord to Main Mast)

Net Tab Authority (torque) = Trim Tab Authority – Moments from Gravity and wingsail

Mast Reactionary Forces

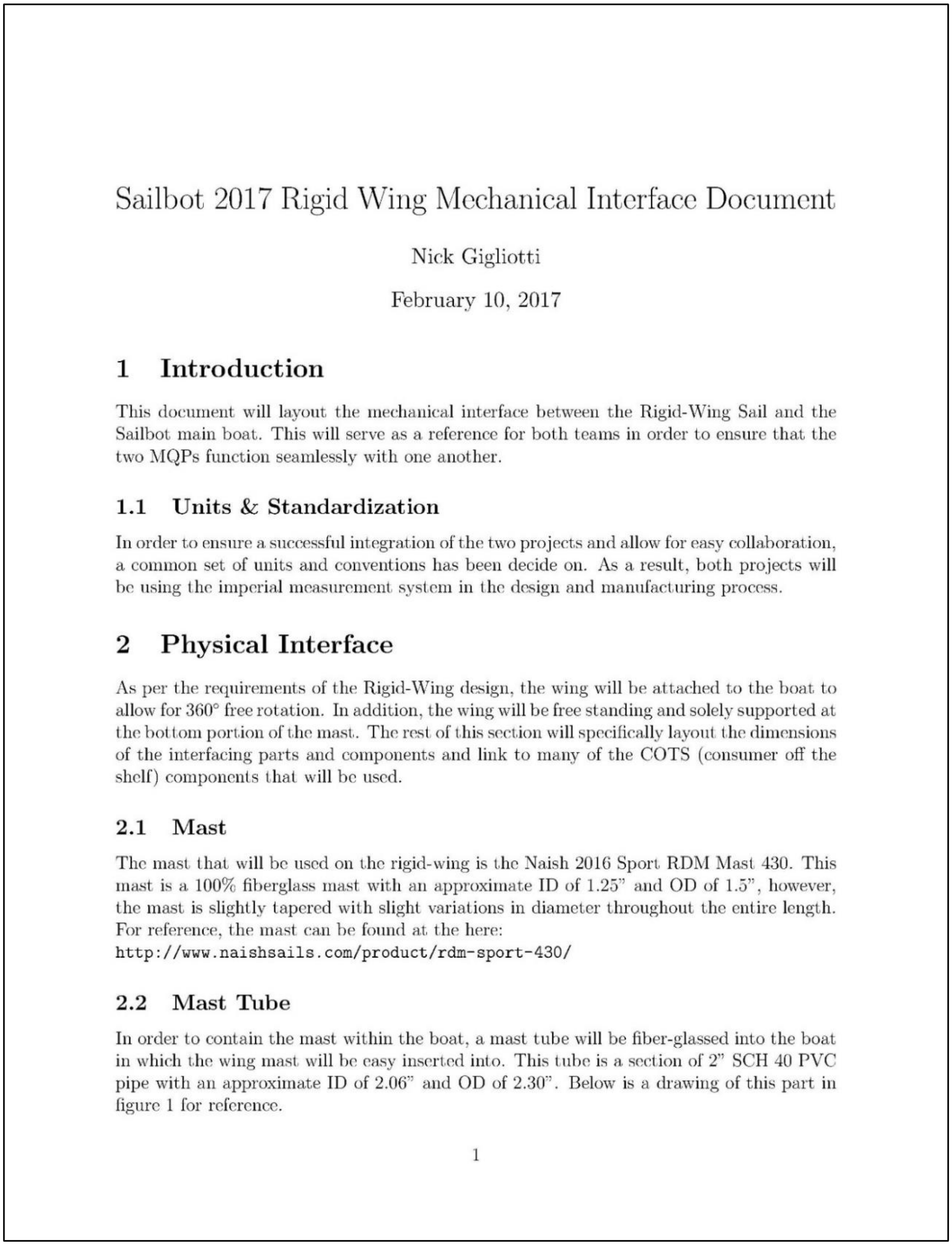
To determine the reaction forces on the mast and the point of fixation, the sum of forces in the x and y directions must be taken, as well as the moment about the z axis. The sum of the forces and moment about any point is equal to zero.

$$\sum \mathrm{F_x} = 0$$

$$\sum F_y = 0$$

$$\sum M_A = 0$$

Appendix F-Collaboration Document



Sailbot 2017 Rigid Wing Mechanical Interface Document

Nick Gigliotti

February 10, 2017

1 Introduction

This document will layout the mechanical interface between the Rigid-Wing Sail and the Sailbot main boat. This will serve as a reference for both teams in order to ensure that the two MQPs function seamlessly with one another.

1.1 Units & Standardization

In order to ensure a successful integration of the two projects and allow for easy collaboration, a common set of units and conventions has been decide on. As a result, both projects will be using the imperial measurement system in the design and manufacturing process.

2 Physical Interface

As per the requirements of the Rigid-Wing design, the wing will be attached to the boat to allow for 360° free rotation. In addition, the wing will be free standing and solely supported at the bottom portion of the mast. The rest of this section will specifically layout the dimensions of the interfacing parts and components and link to many of the COTS (consumer off the shelf) components that will be used.

2.1 Mast

The mast that will be used on the rigid-wing is the Naish 2016 Sport RDM Mast 430. This mast is a 100% fiberglass mast with an approximate ID of 1.25" and OD of 1.5", however, the mast is slightly tapered with slight variations in diameter throughout the entire length. For reference, the mast can be found at the here:
`http://www.naishsails.com/product/rdm-sport-430/`

2.2 Mast Tube

In order to contain the mast within the boat, a mast tube will be fiber-glassed into the boat in which the wing mast will be easy inserted into. This tube is a section of 2" SCH 40 PVC pipe with an approximate ID of 2.06" and OD of 2.30". Below is a drawing of this part in figure 1 for reference.

Figure 71: Collaboration Document 1

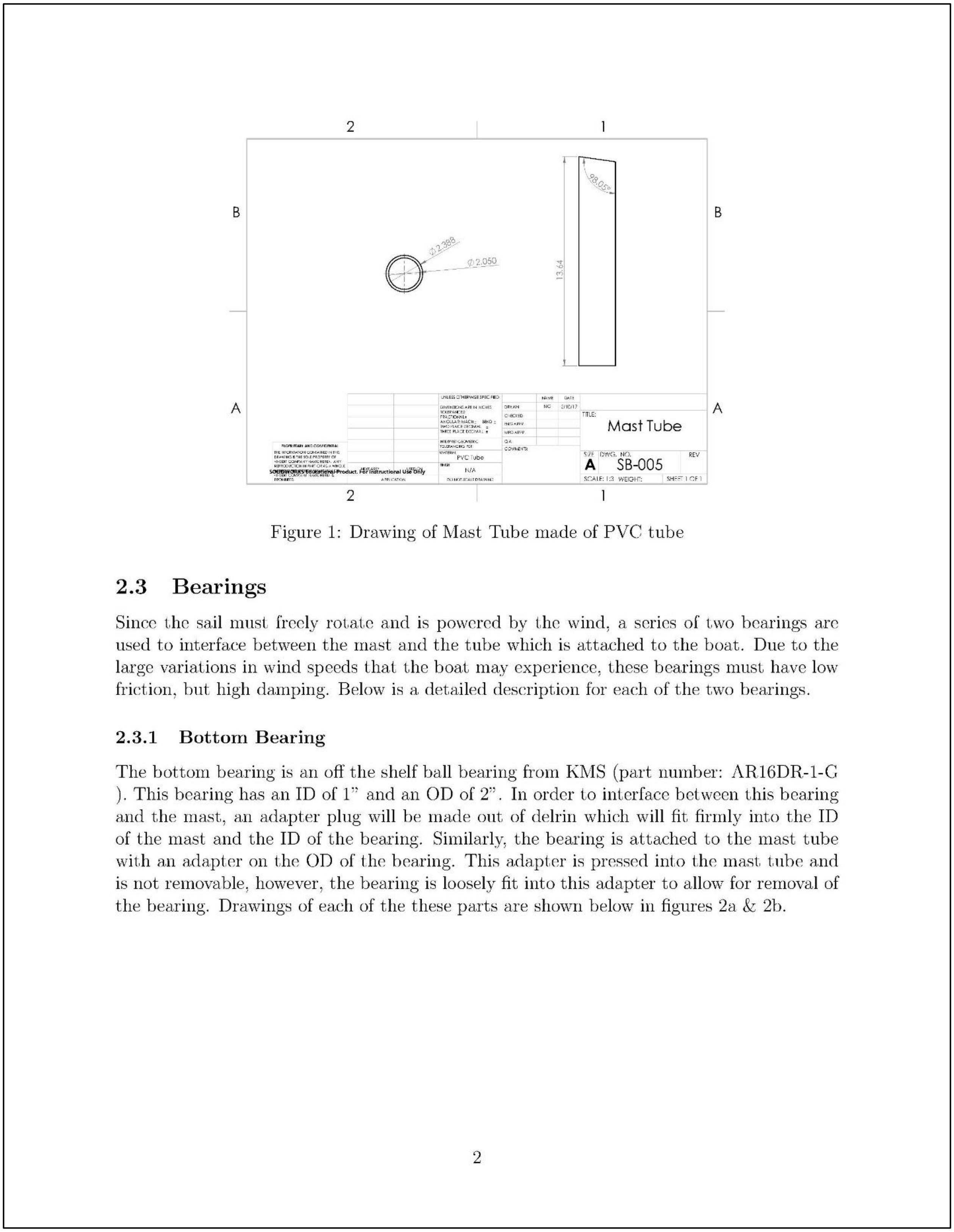


Figure 1: Drawing of Mast Tube made of PVC tube

2.3 Bearings

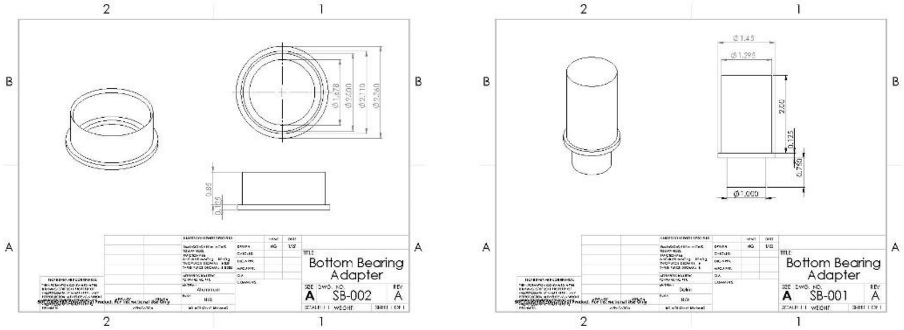
Since the sail must freely rotate and is powered by the wind, a series of two bearings are used to interface between the mast and the tube which is attached to the boat. Due to the large variations in wind speeds that the boat may experience, these bearings must have low friction, but high damping. Below is a detailed description for each of the two bearings.

2.3.1 Bottom Bearing

The bottom bearing is an off the shelf ball bearing from KMS (part number: AR16DR-1-G). This bearing has an ID of 1" and an OD of 2". In order to interface between this bearing and the mast, an adapter plug will be made out of delrin which will fit firmly into the ID of the mast and the ID of the bearing. Similarly, the bearing is attached to the mast tube with an adapter on the OD of the bearing. This adapter is pressed into the mast tube and is not removable, however, the bearing is loosely fit into this adapter to allow for removal of the bearing. Drawings of each of the these parts are shown below in figures 2a & 2b.

2

Figure 72: Collaboration Document 2



(a) Drawing of bottom bearing OD adapter (b) Drawing of bottom bearing ID adapter

Figure 2: Drawings of Bottom Bearing Parts

2.3.2 Top Bearing

The top bearing is a machined delrin bushing that fits around the OD of the mast. This bearing is custom-made to fit onto the mast and provide low-friction rotation. In addition, the mast is sanded smooth in the area of the bearing to provide a better bearing surface for the delrin. A drawing of this bushing is shown below in figure 3.

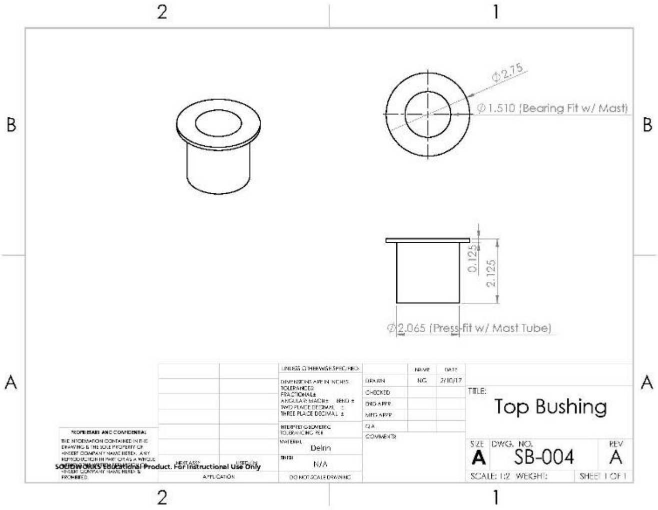
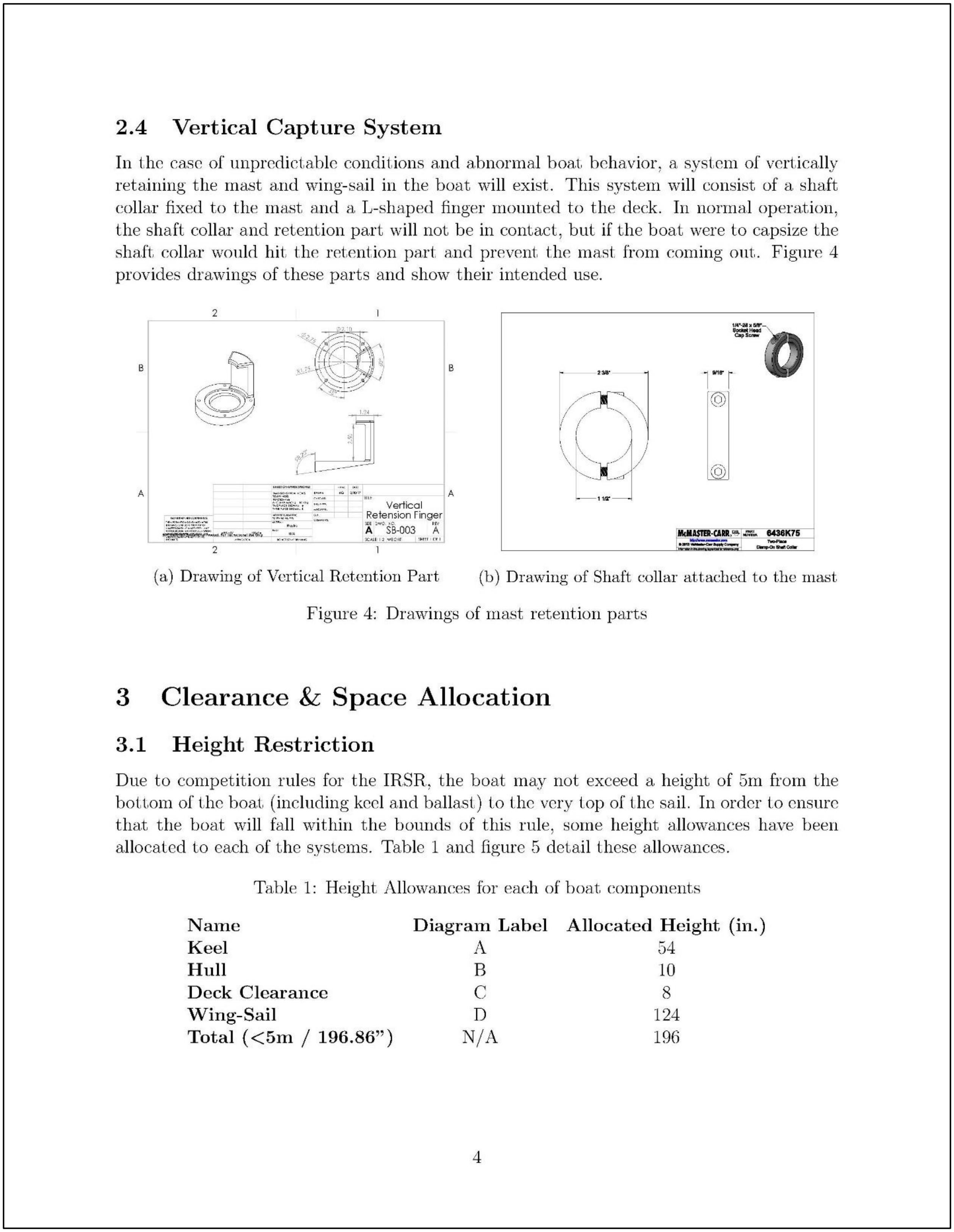


Figure 3: Drawing of top delrin bushing

Figure 73: Collaboration Document 3



2.4 Vertical Capture System

In the case of unpredictable conditions and abnormal boat behavior, a system of vertically retaining the mast and wing-sail in the boat will exist. This system will consist of a shaft collar fixed to the mast and a L-shaped finger mounted to the deck. In normal operation, the shaft collar and retention part will not be in contact, but if the boat were to capsize the shaft collar would hit the retention part and prevent the mast from coming out. Figure 4 provides drawings of these parts and show their intended use.

(a) Drawing of Vertical Retention Part (b) Drawing of Shaft collar attached to the mast

Figure 4: Drawings of mast retention parts

3 Clearance & Space Allocation

3.1 Height Restriction

Due to competition rules for the IRSR, the boat may not exceed a height of 5m from the bottom of the boat (including keel and ballast) to the very top of the sail. In order to ensure that the boat will fall within the bounds of this rule, some height allowances have been allocated to each of the systems. Table 1 and figure 5 detail these allowances.

Table 1: Height Allowances for each of boat components

Name	**Diagram Label**	**Allocated Height (in.)**
Keel	A	54
Hull	B	10
Deck Clearance	C	8
Wing-Sail	D	124
Total (<5m / 196.86")	N/A	196

Figure 74: Collaboration Document 4

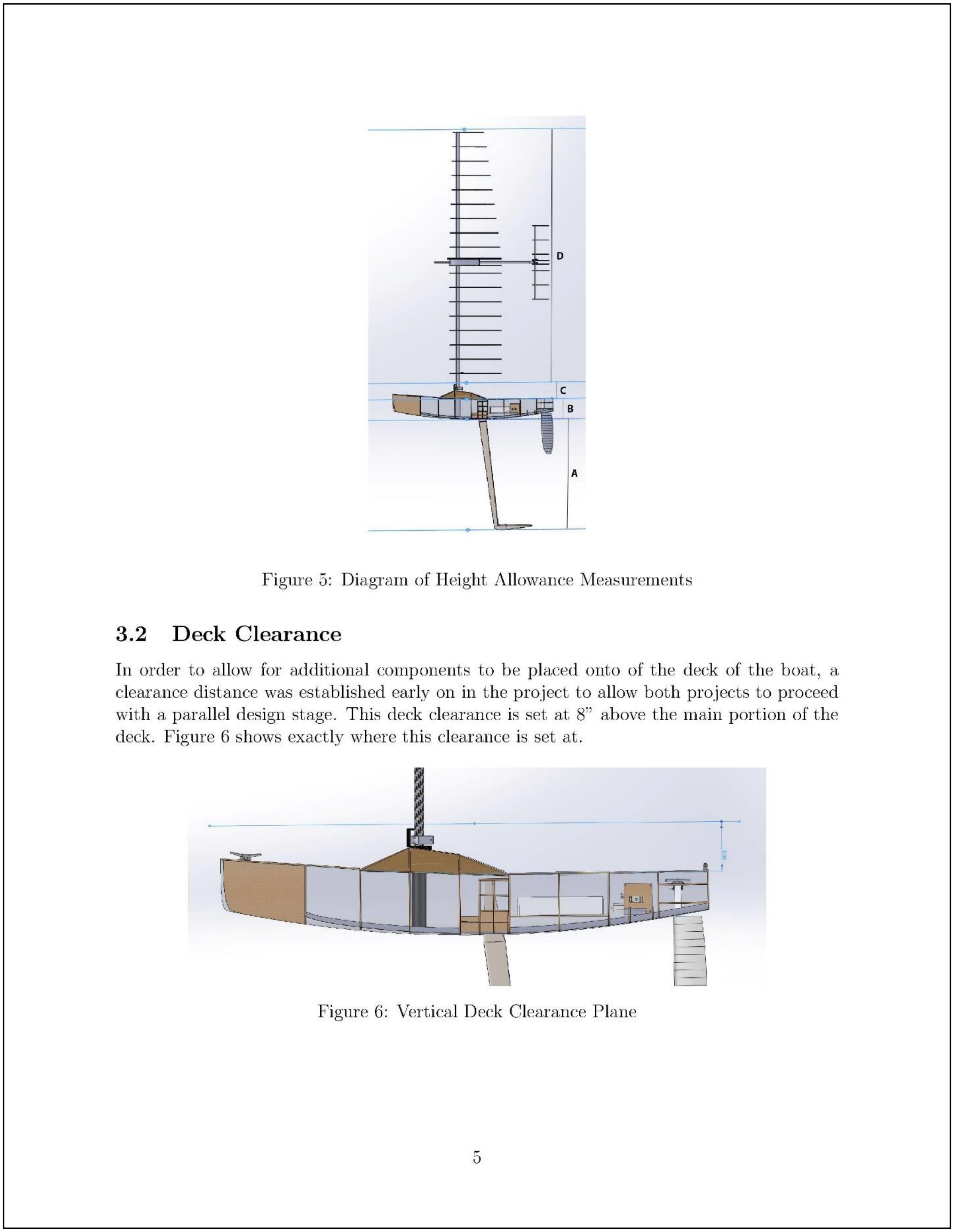


Figure 5: Diagram of Height Allowance Measurements

3.2 Deck Clearance

In order to allow for additional components to be placed onto of the deck of the boat, a clearance distance was established early on in the project to allow both projects to proceed with a parallel design stage. This deck clearance is set at 8" above the main portion of the deck. Figure 6 shows exactly where this clearance is set at.

Figure 6: Vertical Deck Clearance Plane

5

Figure 75: Collaboration Document 5

Appendix G- Code

```
#include <Servo.h>


#define servoOffset 96 //offset to make 0 degrees in code equal to 0 degrees
on the tab

#define maxLiftAngle 30 //angle calculated for maximum lift from wingsail


//Pins for devices

#define potPin A0

#define servoPin 20

#define liftPin 2

#define dragPin 6

#define windSidePin 3

#define led1Pin 36

#define led2Pin 37

#define controlPin 11

#define angleControlPin A3

#define wifiLED 38

#define powerLED 13

#define vInPin A2


#define SSID "sailbot"

#define PASS "Passphrase123"

#define DST_IP "192.168.0.21" //baidu.com

#define DST_PORT 3333



int control = 0; //to enable direct control over tab angle

int lift = 0; //0 to produce no lift 1 to produce lift

int drag = 0;

int windSide = 0; //0 for wind from port 1 for wind from starboard
```

```
int heelIn; //reading from hull heel sensor

int heelAngle = 0; //mapped heel angle, 0 degrees is straight up 90 would be
on its side

int maxHeelAngle = 30;//settable max heel angle


int angleIn;//reading from wind direction sensor on the front of the wingsail

int readAttackAngle; //mapped value from wind sensor

int sentAttackAngle; //value mapped to correct sending format


int controlAngle = 0; //manual angle set by boat


int tabAngle = 0; //angle of tab relative to centered being 0


int count = 0; //count to have leds blink


int state;

int printing = 0;

int tcpConnection = 0;

int connectionCount = 0;


int ledState = LOW;

unsigned long previousMillis = 0;

volatile unsigned long blinkCount = 0; // use volatile for shared variables


int servoAngle;


IntervalTimer LEDtimer;

IntervalTimer servoTimer;


Servo servo;


void setup() {
```

```
  //init
  pinMode(potPin, INPUT);
  pinMode(liftPin, INPUT);
  pinMode(dragPin, INPUT);
  pinMode(windSidePin, INPUT);
  pinMode(controlPin, INPUT);
  pinMode(angleControlPin, INPUT);
  pinMode(led1Pin, OUTPUT);
  pinMode(led2Pin, OUTPUT);
  pinMode(wifiLED, OUTPUT);
  pinMode(powerLED, OUTPUT);
  pinMode(vInPin, INPUT);
  servo.attach(servoPin);

  // Initialize Everything
  initializeComs();
  initializeWifi();

  // Connect to the network
  digitalWrite(wifiLED, LOW);
  connectToNetwork(SSID, PASS);

  LEDtimer.begin(blinkState, 916682);
  servoTimer.begin(servoControl, 50000);

  servo.write(servoOffset); //in place so lift starts at 0 degrees or neutral
state

  digitalWrite(powerLED, HIGH);// turn on power led
}

void loop() {
```

```
//delay(50);  for serial testing no wifi
//--------------------------------------------------------------------------
//Wifi communication and message parsing

if (Serial.available() > 0) {
  // read the incoming byte:
  state = Serial.read() - 48;

  Serial.print("State:");
  Serial.print(state);
}

int vIn = analogRead(vInPin);

if (windSide) {
  servoAngle = tabAngle + 60;
}
else {
  servoAngle = -tabAngle + 60;
}



sentAttackAngle = (360 + readAttackAngle) % 360;

//Serial.print("  Angle of Attack:");
//Serial.print(readAttackAngle);

//Serial.print("  Servo Angle:");
//Serial.println(tabAngle);

stateSet();
```

```
  if (connectedTCP()) {
    connectionCount = 0;
    digitalWrite(wifiLED, HIGH);

    sendBoatMessage(sentAttackAngle, servoAngle, vIn);  //message sent to
hull
    delay(10);                    //delay for message to send before
recieving

    if (readMessage(25)) {
      //Serial.print("S: ");
      //Serial.print(state);
      //Serial.print(", A:");
      //Serial.print(heelAngle);
      //Serial.print(", B:");
      //Serial.print(maxHeelAngle);
      //Serial.print(", C:");
      //Serial.println(controlAngle);
    }

  } else {
    connectionCount++;
    if (connectionCount >= 4) {
      control = 0;
      lift = 0;
      drag = 0;
    }
    openTCP(DST_IP, DST_PORT);    //if no message is recieved than there is
no connection so the port is openend
    delay(50);
  }
}
```

```
void sendBoatMessage(int wind, int servoPos, int volt) {
  String msg = "[";
  msg += addZerosToString(wind, 3) + ",";
  msg += addZerosToString(servoPos, 3) + ",";
  msg += addZerosToString(volt, 3) + "]";

  sendTCPMessage(msg);
}


String addZerosToString(int n, int z) {
  String result = String(n);

  int s = 10;

  while (s < pow(10, z)) {
    if (s >= n) {
      result = "0" + result;
    }
    s = s * 10;
  }

  return result;
}



// This initializes the serial buses
```

```
int initializeComs() {
  Serial.begin(115200);
  Serial4.begin(115200);

  if (printing) Serial.println("Communication Initialized");

  return 0;
}



// This initializes the ESP8266 module
int initializeWifi() {

  // Reset the module
  sendMessageToESP("AT+RST");

  if (printing) Serial.println("Resetting Wifi Module");

  // wait for a "ready" command
  bool reset_successful = waitForStringSerial4("ready", 3000);

  if (reset_successful) {
    if (printing) Serial.println("Wifi Reset Successfully");
    return 0;

  } else {
    if (printing) Serial.println("Wifi Reset Failed");
    return 1;
  }
}
```

```
// This scans for networks and returns a list of networks
int scanForNetworks() {
  // Send the command to print all nearby networks
  sendMessageToESP("AT+CWLAP");

  // TODO: print out all networks
  return 0;
}



// This searches for networks and returns true if the selected network is
found
int searchForNetwork(String networkName) {
  return 0;
}



// This attempts to connect to a network. If it is succesful, True is
returned
bool connectToNetwork(String ssid, String password) {

  if (printing) {
    Serial.println("Attempting to connect to " + ssid);
    Serial.println("Password is " + password);
  }

  // Maybe search for network to see it it's available first?

  // Set the operating mode to Client
```

```
  // Client = 1, AP = 2, Client and AP = 3
  sendMessageToESP("AT+CWMODE=1");

  // Build the message to connect to the given ssid with the password
  String cmd = "AT+CWJAP=\"" + ssid + "\",\"" + password + "\"";
  sendMessageToESP(cmd);

  // wait for a "OK" command
  bool connection_successful = waitForStringSerial4("OK", 3000);

  if (connection_successful) {
    if (printing) Serial.println("Connection Successful");
    return true;

  } else {
    if (printing) Serial.println("Connection Failed");
    return false;
  }
}



// Get ip address if it's connected to a network
String getIP() {
  sendMessageToESP("AT_CIFSR");

  // Sort out IP address
  return "0.0.0.0";
}
```

```
// Open a TCP connection

// A returned value of True indicates it was successful

boolean openTCP(String ip, int port) {

  // Set transparent mode to 1 so that messages recieved will be sent
directly to serial

  // Set transparent mode to 0

  //  sendMessageToESP("AT+CIPMODE=0", printing);


  // build command

  String cmd = "AT+CIPSTART=\"TCP\",\"" + ip + "\"," + port;


  sendMessageToESP(cmd);

  //  Serial.println(cmd);


  // wait for a "OK" command

  bool connection_successful = waitForStringSerial4("OK", 3000);


  if (connection_successful) {

    if (printing) Serial.println("TCP Connection to " + ip + " port number "
+ String(port) + " successful");

    return true;

  } else {

    if (printing) Serial.println("TCP Connection to " + ip + " port number "
+ String(port) + " failed");

    return false;

  }

}





// Send a message over TCP()

void sendTCPMessage(String msg) {
```

```
  // build initial message
  String instructionToSend = "AT+CIPSEND=" + String(msg.length());

  if (printing) Serial.println("Sending message: " + msg);

  // Send the message
  sendMessageToESP(instructionToSend);
  delay(20);
  sendMessageToESP(msg);
}



// Close the current TCP connection
int closeTCP() {
  sendMessageToESP("AT+CIPCLOSE");

  if (printing) Serial.println("TCP Closed");

  return 0;
}



// Return true if connected to TCP, false otherwise
bool connectedTCP() {
  sendMessageToESP("AT+CIPSTATUS");

  if (waitForStringSerial4("STATUS:3", 500)) {
    if (printing) Serial.println("TCP still connected");
    tcpConnection = 1;
    return true;
```

```
  } else {
    if (printing) Serial.println("TCP connection lost");
    tcpConnection = 0;
    return false;
  }
}
```

```
bool readMessage(int timeout) {
  int start_time = millis();

  bool recievedNewData = false;

  //  "[1,180,180,100]"

  while (millis() < start_time + timeout) {
    if (Serial4.available()) {
      String data = Serial4.readString();
      // Serial.println(data);

      for (int i = 0; i < data.length(); i++) {
        if (data.substring(i, i + 1) == "[") {
          if (data.length() > i + 15) {
            String validData = data.substring(i, i + 15);

            // Serial.println("Special string: " + validData);
            state =             validData.substring(1, 2).toInt();
```

```
          heelAngle =         validData.substring(3, 6).toInt();
          maxHeelAngle =      validData.substring(7, 10).toInt();
          controlAngle =   validData.substring(11, 14).toInt();

          recievedNewData = true;
        }
      }
    }
  }
}

  return recievedNewData;
}
```

```
void sendMessageToESP(String commandToSend) {
  Serial4.println(commandToSend);

  if (printing >= 2) Serial.println("--- " + commandToSend);
}
```

```
// This method scans the input from Serial4 for a specific key
// If this key is found before the timeout, true is returned.
// Othertime false is returned
bool waitForStringSerial4(String key, int timeout) {

  int start_time = millis();

  while (millis() < start_time + timeout) {
    if (Serial4.available()) {
      String data = Serial4.readString();
      // Serial.println(data);

      for (int i = 0; i < data.length() - key.length(); i++) {
        if (data.substring(i, i + key.length()) == key) {
          return true;
        }
      }
    }
  }

  return false;
}

void blinkState() {
  if (ledState == LOW) {
    ledState = HIGH;
    blinkCount = blinkCount + 1;  // increase when LED turns on
  } else {
    ledState = LOW;
  }
  if (!tcpConnection) {
```

```
    digitalWrite(wifiLED, ledState);
  }
  if (lift) {
    if (windSide) {
      digitalWrite(led1Pin, HIGH);
      digitalWrite(led2Pin, LOW);
    }
    else {
      digitalWrite(led2Pin, LOW);
      digitalWrite(led1Pin, ledState);
    }
  }
  if (drag) {
    if (windSide) {
      digitalWrite(led2Pin, HIGH);
      digitalWrite(led1Pin, LOW);
    }
    else {
      digitalWrite(led1Pin, LOW);
      digitalWrite(led2Pin, ledState);
    }
  }
}

void stateSet() {
  if (state == 0) {
    control = 0;
    lift = 0;
    drag = 0;
  }
  else if (state == 1) {
    control = 0;
```

```
    lift = 1;
    drag = 0;
    windSide = 1;
  }
  else if (state == 2) {
    control = 0;
    lift = 1;
    drag = 0;
    windSide = 0;
  }
  else if (state == 3) {
    control = 0;
    lift = 0;
    drag = 1;
    windSide = 1;
  }
  else if (state == 4) {
    control = 0;
    lift = 0;
    drag = 1;
    windSide = 0;
  }
  else if (state == 5) {
    control = 1;
    lift = 0;
    drag = 0;
  }
}

void servoControl() {

  angleIn = analogRead(potPin); // reads angle of attack data
```

```
  readAttackAngle = angleIn * 0.3442 - 122.93;
  //-----------------------------------------------------------------------------
--------------------------
  //set for manual control
  if (control) {
    digitalWrite(led1Pin, HIGH);
    digitalWrite(led2Pin, HIGH);
    servo.write(servoOffset + controlAngle);
  }

  //-----------------------------------------------------------------------------
-----------------------------
  //when lift is desired
  if (lift) {

    if (!windSide) {
      readAttackAngle = readAttackAngle * -1;
    }

    //if the lift angle isnt enough and the heel angle isnt too much the
angle of attack is increased
    if ((maxLiftAngle > readAttackAngle+1)) {  //&& (abs(heelAngle) <=
maxHeelAngle))) {
      if (tabAngle >= 55) { }
      else {
        tabAngle++;
      }
    }

    //if the lift angle is too much or the max heel angle is too much the
wingsail lightens up
    else if ((maxLiftAngle < readAttackAngle)) {  //&& (abs(heelAngle) <=
maxHeelAngle)) || (abs(heelAngle) >= maxHeelAngle)) {
      if (tabAngle <= -55) {  }
```

```
      else {
        tabAngle--;
      }
    }

    //if the angle of attack is correct
    else if (maxLiftAngle == readAttackAngle) { }

    //to adjust tab angle according to wind side
    if (windSide) {
      servo.write(servoOffset + tabAngle);
    }
    else {
      servo.write(servoOffset - tabAngle);
    }
  }
  //-------------------------------------------------------------------------
----------------------------------
  //while drag if desired
  if (drag) {


    //set sail to most possible angle of attack with respect to direction of
wind
    if (windSide) {
      servo.write(servoOffset + 55);
    }
    else if (!windSide) {
      servo.write(servoOffset - 55);
    }
  }
  //-------------------------------------------------------------------------
---------
  //minimum lift (windvane)
```

```
  if (!lift && !drag && !control) {
    digitalWrite(led1Pin, LOW);
    digitalWrite(led2Pin, LOW);

    servo.write(servoOffset);
    /*
      if (readAttackAngle < 2 && readAttackAngle > -2) {  }            // if
angle of attack is within -2 to 2 do nothing
      else if (readAttackAngle > 2 && tabAngle < 60) {       // if angle of
attack is to much adjust
      tabAngle--;
      }
      else if (readAttackAngle < -2 && tabAngle > -60) { // if angle of
attack is to much adjust
      tabAngle++;
      }
      servo.write(servoOffset + tabAngle);
    */
  }
}
```

References

Bending Moment and Shear Force Diagram Calculator. N.p., n.d. Web. 19 Mar. 2017.

"Greenbird." Greenbird. Ecotricity, n.d. Web. 19 Mar. 2017.

"Masts." Masts. N.p., n.d. Web. 14 Mar. 2017.

Sailbot.org. N.p., n.d. Web. 19 Mar. 2017.

SailWorks. Hood River, Oregon: SailWorks, 2015. 2015. Web.

Networks, Inc. Bump. "RDM Sport 290." Naish Windsurfing | Windsurf Sails, Windsurf Boards, Booms, Masts, Rigs, Soft Tech and more! N.p., n.d. Web. 10 Mar. 2017.