AUTONOMOUS SAILBOAT

ECE 445 Design Document

Team 2

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1 Introduction

1.1 Problem

WRSC (World Robotic Sailing Championship) is an autonomous sailboat competition that aims at stimulating the development of autonomous marine robotics. Unlike the more traditional problem of autonomous radio controlled (RC) vehicles, autonomous sailboats pose a more challenging control problem – dual-mode capability. In the event that the autonomous system cannot navigate a difficult environment (harsh winds, etc.), the user must have the skill to manually control the boat back to base. The user would have difficulty retrieving the boat otherwise. Furthermore, the convoluted steering system on RC sailboats presents a steep learning curve. Amateur users greatly benefit from this dual-mode capability and are less likely to potentially lose their sailboat to the wind or waves. Additionally, autonomous sailboats attract great attention due to their possible infinite endurance [1]. The few autonomous sailboat designs that exist utilize expensive and scarce autopilot systems such as the Pixhawk Flight controller.

1.2 Solution

Unlike the few designs on the market, our design will rely on low-cost sensors that are easy to set up and install into any standard RC sailboat. The affordability of our design contributes to its marketability among amateur users who are not willing to spend the extra money on alternative systems. Thus, the sailboat will offer a "return to base" feature that would diminish concern of an amateur losing their boat via lack of steering ability. Experienced users will also benefit from this feature as the sailboat will automatically return to base if it has detected that it is out of range from the RC controller.

Users will also be able to monitor real-time sensor data that will be critical in tuning the autonomous steering feature of the sailboat and potentially useful in understanding manual control. This ground control system will receive this data from the on-board MCU via a telemetry transceiver. The only communication the operator will maintain with the sailboat is via the RC remote control. The remote control features two joysticks for manually steering the boat and 3 buttons for toggling autonomous mode, returning the sailboat to base, and setting a new base position.

1.3 Visual Aid

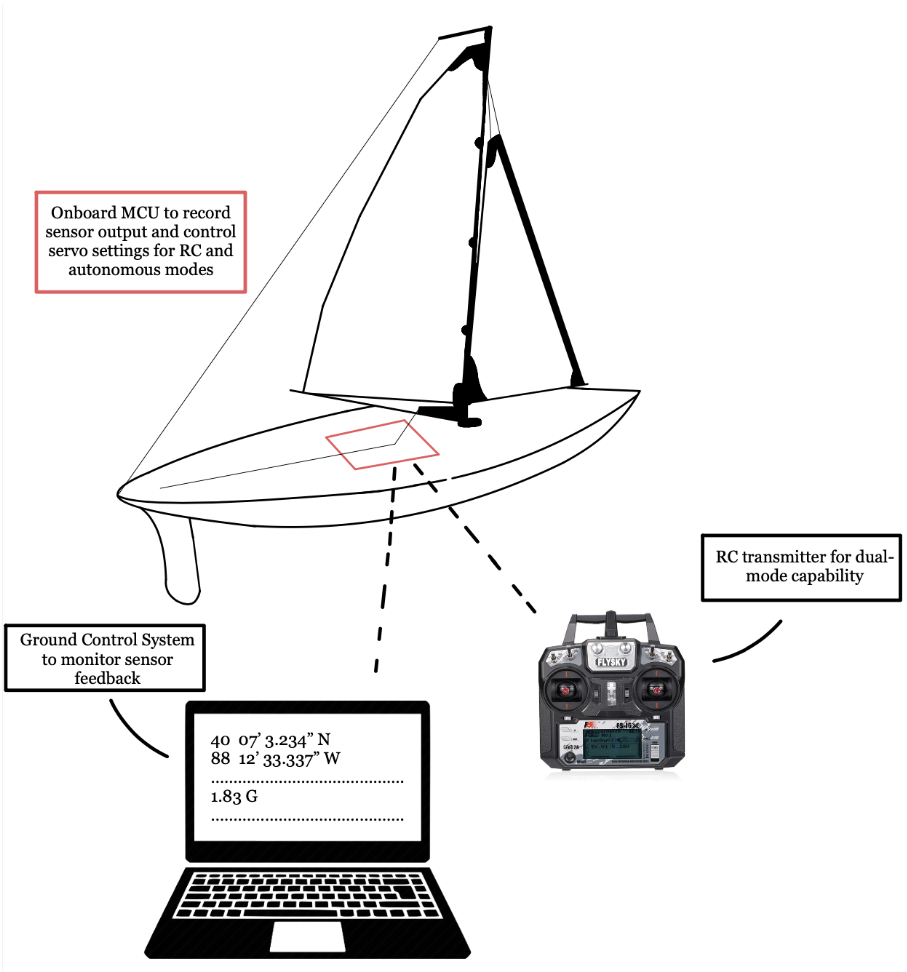

Figure 1: Visual Aid

1.4 High Level Requirements

- The sailboat can be manually controlled via remote control and can autonomously maintain a compass heading within ±9°.
- The sailboat can record and transmit its GPS coordinates, compass heading, speed and wind direction back to the operator with a latency of less than 1 s.
- The sailboat features a "return to base" option that will autonomously guide the sailboat back to a set base position within a 5 m range. The base is initially set to the position in which the boat is turned on and is defined by GPS coordinates.

2 Design

2.1 Block Diagram

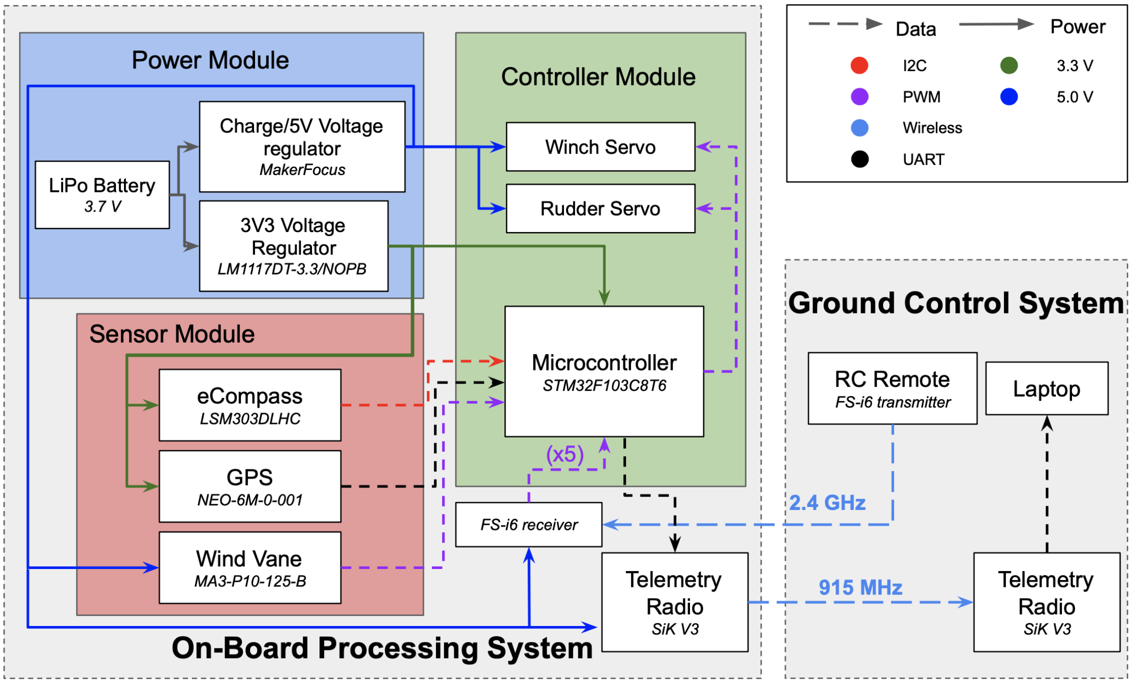

Figure 2: Block Diagram

2.2 Functional Overview and Subsystem Requirements

2.2.1 On-Board Processing System

The On-Board Processing System is consists of the power subsystem, controller subsystem and sensor subsystem. It is responsible for processing data from the sensors and adjusting the winch and rudder servo accordingly to steer the sailboat manually or autonomously.

The power subsystem is responsible for supplying power to all electrical components that are on-board the sailboat. In order to handle the varying voltage requirements between components, there are two voltage regulators. A 3.7 V LiPo battery is used as the primary supply voltage; one voltage regulator increases this voltage to 5 V and can be used to charge the LiPo battery. The other voltage regulator decreases the supply voltage to 3.3 V. The varying voltage requirements for each component can be seen in Figure 2.

The controller subsystem is responsible for processing the output data from the sensor subsystem and operator input via the FS-i6 receiver. When in manual mode, it will just adjust the sail and rudder angles based on the FS -i6 controller input. When in autonomous mode, it will change the sail and rudder directions such that it does not deviate more than ±9°. This mode of operation will be further explained in the autonomous steering section. The MCU outputs two PWM signals for the winch and rudder servo to steer the sailboat. It also outputs the sensor data to the telemetry radio so that the data can be displayed in the ground control system.

The sensor subsystem is responsible for gathering essential data that the controller module will use to determine how to control the sailboat. The wind vane captures the apparent wind angle, the GPS captures the GPS coordinates of the sailboat and the eCompass captures the acceleration and compass heading. When the user presses the set base button, the GPS coordinates are used to set the new base position. Similarly, the MCU compares the current GPS coordinates with the base position coordinates when the user triggers the return to base feature. The apparent wind angle and compass heading are primarily used by the MCU in deciding how to adjust the sail and rudder to achieve a heading. Furthermore, the acceleration will be useful in adjusting the steering algorithms to achieve maximum efficiency.

Table 1: On-Board Processing System Requirements and Verification Pt 1.

Requirements	Verification
• The processing system must prevent the user from activating the return to base feature when it is not in autonomous mode. Furthermore, the processing system must prevent the operator from controlling the rudder and winch servos when in autonomous mode.	• Place the sailboat on the lazy susan, turn off the box fan simulating the wind. Turn on the sailboat and flip the autonomous mode switch ON. Move the two joysticks to control the rudder and winch servo. Verify that the servos do not respond to the movement of the joysticks. • Place the sailboat ≥ 5 m away from the lazy susan. Turn on the sailboat, the base position should now be visibly set in Mission Planner. Place the sailboat on the lazy susan and flip the autonomous mode switch ON. Trigger the return to base feature and verify that the servos do not respond to the movement of the joysticks.
• The processing system must prevent the return to base feature to be triggered if the base position is ≤ 5 m of the sailboat's current GPS location.	• Turn on the sailboat and verify that the base position is set via Mission Planner. Move the sailboat ≤ 5 m in any direction and press the return to base button. • Verify that return to base has not been triggered by moving either of the joysticks to control the winch or servo. If either joystick controls its respective servo, return to base has not been triggered. Repeat testing within any range ≤ 5 m of the set base position.

Table 2: On-Board Processing System Requirements and Verification Pt 2.

• The processing system correctly adjusts the sail and rudder angle according to Table 4 within a tolerance of 2°.	• Place the sailboat on the lazy susan such that its heading is aligned with 0°. Place a box fan directly in front of the lazy susan such that the wind direction is directly ”upwind” of the sailboat. Measure the current sail and rudder angle using the compass on the lazy susan. • Now, rotate the sailboat such that its heading aligns with an apparent wind angle of your choosing. Allow the sailboat to rotate the sail and rudder then turn off the sailboat. Measure the sail and rudder angle again and compare to initial measurements. • Using Table 4 for sail and rudder angles, verify that the angles match for the apparent wind angle chosen previously (what heading you rotated the boat to).

2.2.2 Ground Control Subsystem

The ground control subsystem is responsible for providing the operator with manual control of the sailboat. It also provides the operator with autonomous mode switches and provides a display of useful sensor feedback data from the sailboat. This will be useful to helping the operator understand manual control and in adjusting the autonomous mode features.

The SiK V3 telemetry radio receiver connects to the user's laptop via USB. ArduPilot Mission Planner is configured to read data from the receiver and display the sailboat's GPS coordinates, acceleration, compass heading and the base position and wind direction.

Five channels of the FS-i6 remote control transmitter are used to send PWM input signals to the sailboat. Two of these channels are used for the winch and rudder servo and can be controlled via the 2 joysticks on the remote control. One switch will toggle autonomous mode and 2 buttons will be used to set the base position and trigger the return to base feature.

Table 3: Ground Control Subsystem Requirements and Verification

Requirements	**Verification**
• The ground control system displays updated sensor data with a feedback delay ≤ 1 s.	• Turn on sailboat and note base position on laptop display. Turn off sailboat and repeat at a location approximately 10 m away from starting location. Then, turn on sailboat and walk back to starting position; verify the GPS coordinates match initial measurement within 1 s. • Place sailboat on lazy susan such that its heading lines up with 0°. Turn on the sailboat and adjust the lazy susan such that the compass heading viewed on the laptop display reads North. Rotate the sailboat 90°, 180°, and -90°. Verify that the compass heading reads East, South and West respectively within 1 s.

2.3 Autonomous Steering

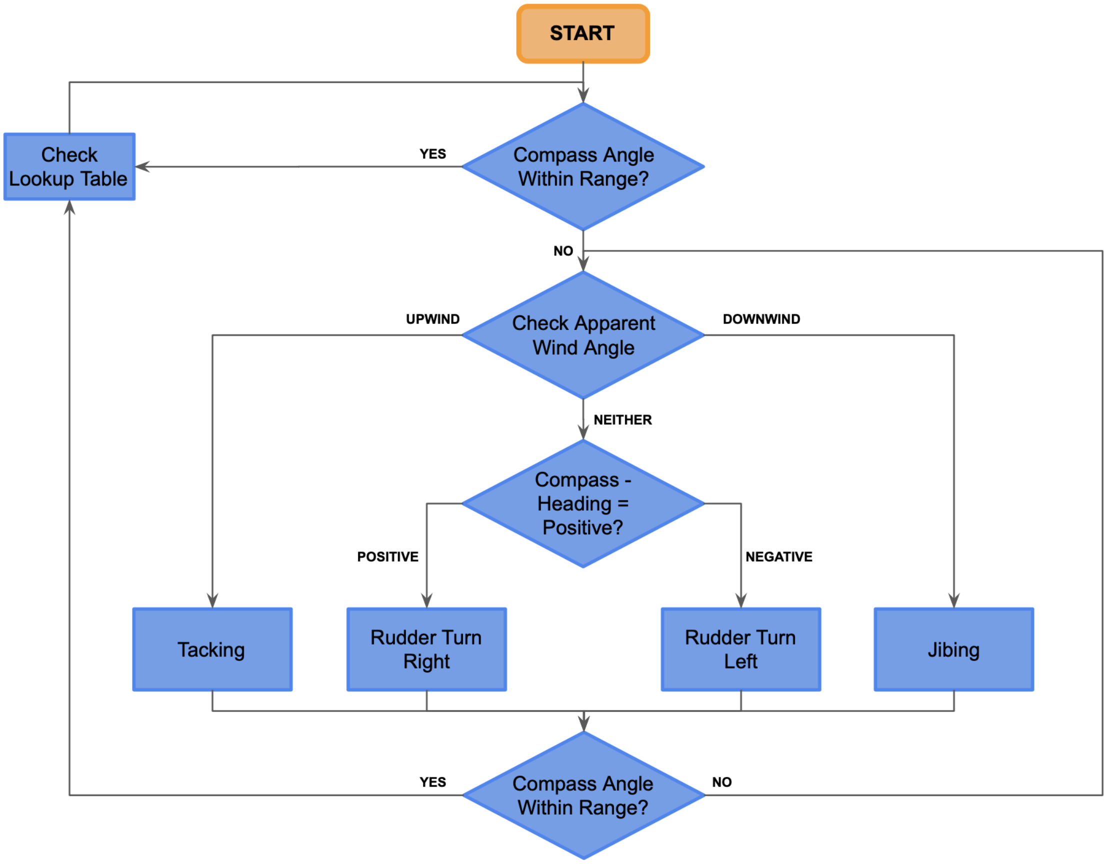

Figure 3: High Level Flow Chart

The On-Board Processing System follows the control flow diagram shown in Figure 3. The lookup table as shown in Table 4 is used to compare the apparent wind angle to get the new sail angle. This occurs while the compass heading deviates $\leq \phi_0$ from the desired heading. Otherwise, the system will check the wind direction and carry out turning (using the rudder) or tacking and jibing. This will occur until the compass heading is back into the desired range.

Table 4: Sail and Rudder Angle Lookup Table

Apparent Wind Angle	Point of Sail	Sail Angle	Rudder Angle
$0 \leq \theta \leq 45 \| \| 315 \leq \theta \leq 360$	No-Go Zone	0°	Tacking
$45 \leq \theta \leq 75$	Close-Hauled	15°	0°
$75 \leq \theta \leq 105$	Beam Reach	-45°	0°
$105 \leq \theta \leq 135$	Broad Reach	-60°	0°
$135 \leq \theta \leq 225$	Running	±90°	0°
$225 \leq \theta \leq 255$	Broad-Reach	60°	0°
$255 \leq \theta \leq 285$	Beam Reach	45°	0°
$285 \leq \theta \leq 315$	Close-Hauled	15°	0°

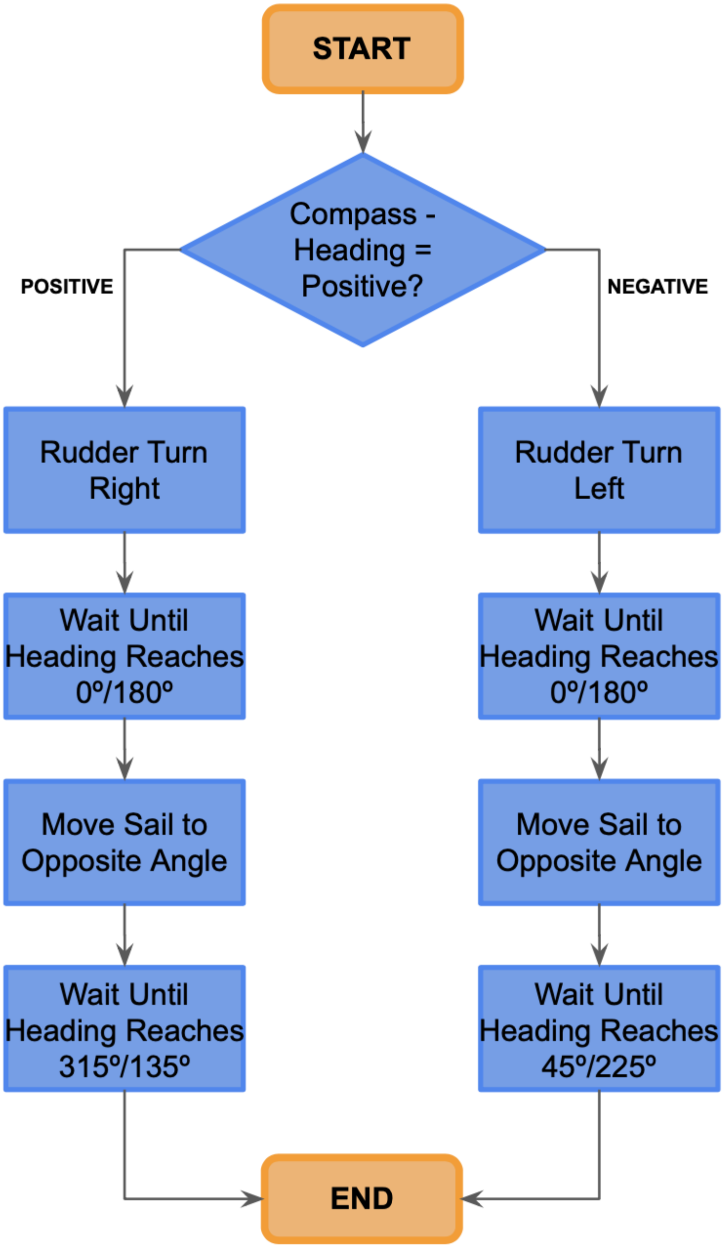

Figure 4: Tacking and Jibing Flow Chart

The tacking and jibing function checks the deviation of the boat and turns the rudder accordingly. It then moves the sail to the opposite position to finish the maneuver successfully.

2.4 Tolerance Analysis

For the tolerance analysis, a simple mathematical model for the sailboat has been created to ensure that our sailboat will maintain a $\leq \pm 9$ deviation from the desired heading. There are some assumptions that were made:

- Waves are ignored
- The modulus of the lift force in the sail is approximately constant.
- The modulus of the force in the rudder is approximately constant
- The roll and pitch angles are approximately 0.
- Fluid friction generated by the water is ignored.
- Yaw angle variation does not affect the forces.
- The movement of the sail barely changes the center of mass of the system, G.

This is a free body diagram of the sailboat taking into account the assumptions:

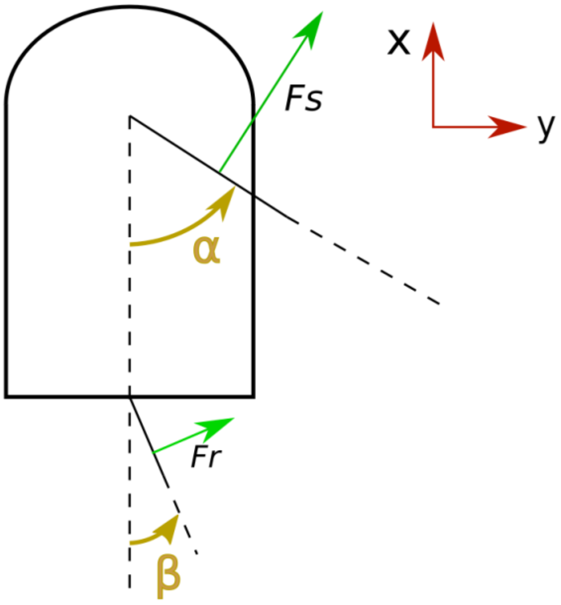

Figure 5: Free body diagram of the sailboat

With this body diagram, a mathematical model for the sailboat can be easily derived using Newton's laws for rotation and movement (note the direction of forces Fr and Fs changes when beta ¡ 0 and alpha ¡ 0 respectively):

$$if\,(\alpha, \beta > 0) : x := F_s|\sin\alpha| - F_r|\sin\beta| = m\frac{d^2x}{d^2t} \tag{1}$$

$$y := F_s|\cos\alpha| - F_r|\cos\beta| = m\frac{d^2y}{d^2t} \tag{2}$$

$$F_s|\cos\alpha|x_{gs} + F_s|\sin\alpha|y_{gs} - F_r|\cos\beta|x_{gr} - F_r|\sin\alpha|y_{gr} = M\frac{d^2\phi}{d^2t} \tag{3}$$

$$if\,(\alpha < 0, \beta > 0) : x := F_s|\sin\alpha| - F_r|\sin\beta| = m\frac{d^2x}{d^2t} \tag{4}$$

$$y := -F_s|\cos\alpha| - F_r|\cos\beta| = m\frac{d^2y}{d^2t} \tag{5}$$

$$-F_s|\cos\alpha|x_{gs} - F_s|\sin\alpha|y_{gs} - F_r|\cos\beta|x_{gr} - F_r|\sin\alpha|y_{gr} = M\frac{d^2\phi}{d^2t} \tag{6}$$

$$if\,(\alpha < 0, \beta < 0) : x := F_s|\sin\alpha| - F_r|\sin\beta| = m\frac{d^2x}{d^2t} \tag{7}$$

$$y := -F_s|\cos\alpha| + F_r|\cos\beta| = m\frac{d^2y}{d^2t} \tag{8}$$

$$-F_s|\cos\alpha|x_{gs} - F_s|\sin\alpha|y_{gs} + F_r|\cos\beta|x_{gr} + F_r|\sin\alpha|y_{gr} = M\frac{d^2\phi}{d^2t} \tag{9}$$

$$if\,(\alpha > 0, \beta < 0) : x := F_s|\sin\alpha| - F_r|\sin\beta| = m\frac{d^2x}{d^2t} \tag{10}$$

$$y := F_s|\cos\alpha| + F_r|\cos\beta| = m\frac{d^2y}{d^2t} \tag{11}$$

$$F_s|\cos\alpha|x_{gs} + F_s|\sin\alpha|y_{gs} + F_r|\cos\beta|x_{gr} + F_r|\sin\alpha|y_{gr} = M\frac{d^2\phi}{d^2t} \tag{12}$$

$$x_{gs} := \frac{L}{2}|\cos\alpha| \tag{13}$$

$$y_{gs} := \frac{L}{2}|\sin\alpha| \tag{14}$$

$$x_{gr} := l + \frac{r}{2}|\cos\beta| \tag{15}$$

$$y_{gr} := \frac{r}{2}|\sin\beta| \tag{16}$$

Where m is the mass of the sailboat, M is the moment of inertia of the sailboat, F_s and F_r are the forces in the sail and in the rudder, α is the sail angle, β is the rudder angle, $x_g s$

is the distance between the center of mass and the point of application of F_s in the x-axis, y_gs is the distance between the center of mass and the point of application of F_s in the y-axis, x_gr is the distance between the center of mass and the point of application of F_r in the x-axis, y_gr is the distance between the center of mass and the point of application of F_r in the y-axis, L is the length of the sail, l is the distance between the center of mass and the rudder and r is the length of the rudder and ϕ is the compass heading variation angle $(CompassHeading_{initial} - CompassHeading_{actual})$.

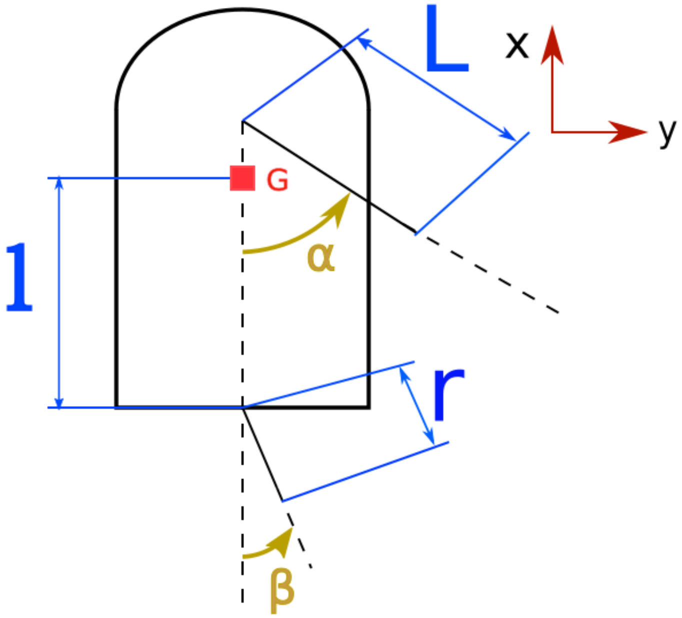

Figure 6: Depiction of variables L, l and r

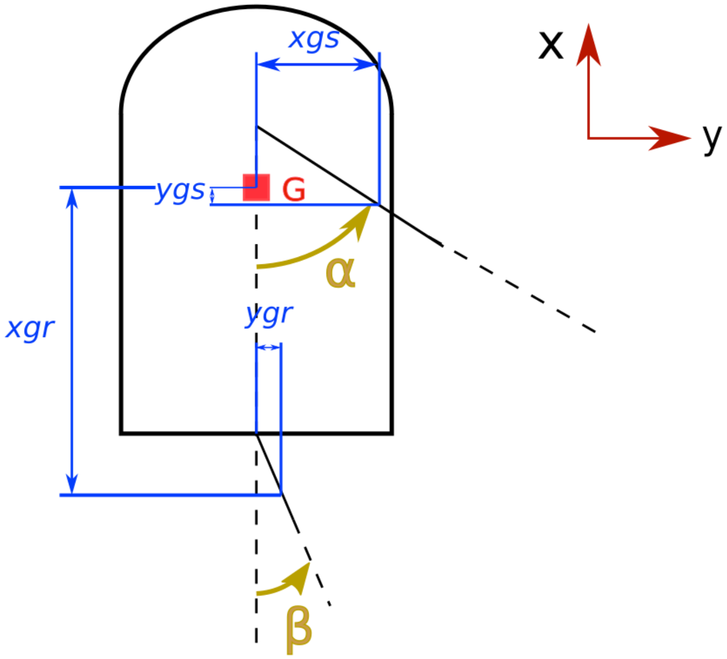

Figure 7: Depiction of variables x_gr, x_gs, y_gr and y_gs

To come up with an approximate solution for the differential equations, the equations 17 - 22 were used.

$$F = m\frac{d^2x}{d^2t} \tag{17}$$

$$v(t) = \int_0^t \frac{F(t)dt}{m} \approx \int_0^{t-t_0} \frac{F(t)dt}{m} + F(t)t_0 \tag{18}$$

$$x(t) = \int_0^t v_x(t)dt \approx \int_0^{t-t_0} v_x(t)dt + v_x(t)t_0 \tag{19}$$

$$y(t) = \int_0^t v_y(t)dt \approx \int_0^{t-t_0} v_y(t)dt + v_y(t)t_0 \tag{20}$$

$$w(t) = \frac{\int_0^t T(t)dt}{M} \approx \int_0^{t-t_0} T(t)dt + T(t)t_0 \tag{21}$$

$$\phi(t) = \int_0^t w(t)dt \approx \int_0^{t-t_0} w(t)dt + w(t)t_0 \tag{22}$$

To come up with what phi_0 angle should trigger the control, several simulations were made using different values for the phi_0 angle. It was found that a $phi_0 \approx 4^\circ$, keeps the sailboat within the desired compass heading.

2.5 Cost Analysis and Task Schedule

The average salary of an ECE graduate is $79,714/year [2]. The average person works 2080 hours per year. $79,714/2080 = $38.32/hour. Each member of the group will work an average of 10 hours per week in the project. 10 hours/week * 10 weeks = 100 hours. Therefore, the total labor cost of this project comes to a total of **$11,496**.

This project will take the machine shop about 15 hours. According to UIUC's machine shop website, the average pay is $36.65/hr plus materials [3]. Therefore, the total machine shop cost is 15hr x $36.65/hr = **$549.75**.

As shown in Table 5, the total parts cost comes to **$251.83**.

Total project cost = Parts + Machine Shop + Labor = $251.83 + $549.75 + $11,496 = **$12297.58**.

Table 5: Parts Cost

Part	Manufacturer	Part Number	Quantity	Extended Cost
Microcontroller	STMicroelectronics	STM32F103C8T6	1	$7.00
Sail Winch Servo	Joysway Hobby	880545	1	$25.95
Rudder Servo	Joysway Hobby	881504	1	$9.95
BJT Transistor	Micro Commercial Co	2N3904-AP	4	$1.36
4.7 KΩ Resistor	YAGEO	RC1206FR-104K7L	4	$0.40
1 KΩ Resistor	YAGEO	RC1206FR-101KL	2	$0.20
3 Pin Male Header	Molex	0022284036	2	$0.74
5 V Converter	MakerFocus	B07PZT3ZW2	1	$2.35
3V3 Regulator	Texas Instruments	LM1117DT-3.3/NOPB-ND	1	$1.89
2 Pin Male Header	Molex	0022284028	3	$0.87
10 µF Capacitor	Smasung Electro-Mechanics	CL21B106KPQNFNE	2	$0.58
4.7 µF Capacitor	Smasung Electro-Mechanics	CL10A475KQ8NNWC	1	$0.10
100 nF Capacitor	KEMET	C0603C104K8PAC7867	5	$1.00
GPS Module	Hiletgo	GY-NEO6MV2	1	$17.49
Wind Vane Encoder	US Digital	MA3-P10-125-B	1	$60.22
eCompass	Hiletgo	GY-511 LSM303DLHC	1	$7.99
ARM 10 Pin Connector	Amphenol CS	G821EU210AGM00Y	1	$0.75
Telemetry Radio	Holybro	SiK V3 17012	1	$56.00
RC Controller	FlySky	FS-i6 6CH	1	$38.00
Receiver	FlySky	FS-iA6	1	$18.99

Table 6: Weekly Schedule

Date	**Tasks Overview**	**Riley**	**Lorenzo**	**Arthur**
2/21	Design Document Check, Order Parts	STM32 research, Design Document	Circuit Schematic, PCB Design	Physical Design, Design Document
2/28	Design review, PCB board reviews	Sensor module unit testing, PCB design	Power module unit testing, PCB design	Controller module unit testing
3/14	Individual autonomous software design	STM32Cube setup, HAL library	Servo control with BluePill	Sensor input with BluePill
3/21	Finish design using BluePill dev board	Sensors and Servo STM32Cube Libraries	Sensors and Servo STM32Cube Libraries	Sensors and Servo STM32Cube Libraries
3/28	Implement return to base feature with BluePill dev board	STM32Cube Autonomous mode libraries	Configuring servo module with BluePill	Configuring controller module with BluePill
4/4	Transfer implementation to PCB	Programming PCB	Constructing boat with PCB	Soldering PCB
4/11	Adjust sensors and algorithms	Optimize servo adjustment algorithms	Optimize efficiency of servos	Optimize efficiency of controller
4/11- 5/2	Mock demo, demonstration, presentation, final paper	Final adjustments, Final Paper	Final adjustments, Final Paper	Final adjustments, Final Paper

3 Ethics and Safety

There are a few ethics policies that we need to take into consideration with this project. Section 7.6 of the IEEE Code of Ethics I.5 states, “to seek, accept, and offer honest criticism of technical work… and to credit properly the contributions of others” [4]. As our project is not the first design for an autonomous sailboat, we ensure to credit any sources from previous projects and credit any resources we build upon [5]. Our project is a challenging assignment for the members of our team; we will strive to make use of any constructive criticism along the way.

Furthermore, there are a few safety concerns our team needs to address. As the sailboat will have an on-board power supply, we must ensure that the casing of the power subsystem is completely waterproof and does not pose any risk for electrical shock. We will also ensure that wire connections from the servos to our waterproof casing are robustly secured to resist vibration and rolling as the sailboat may face on-board water exposure. Finally, our ground control system application will allow users to monitor the sensor data from the sailboat. Such data as the GPS coordinates of the boat, and hence user, poses a risk to their privacy. We will ensure that this application protects and does not monitor the user’s data. Through ensuring safety we abide to uphold IEEE standards I.1; “to hold paramount, the safety, health, and welfare of the public… and to protect the privacy of others” [2].

Finally, our team will ensure to follow Lab Safety guidelines in testing our circuits and sensors. We will also abide by COVID-19 CDC recommended safety guidelines as we meet in person to work on the project.

4 References

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