Autonomous Sailboat

Design Document

Austin Glass

Devansh Damani

Michael Sutanto

Team 24

TA: Koushik Udayachandran

Prof: Dr. Fliflet

Table of Contents

1. Introduction

1.1 Problem:

Sailboats navigate from one location to another powered only by the environment around it - the wind and water current. Compared to motor powered boats, they have far less control over their desired path, only able to control a limited range of motion depending on the positioning of the mast and rudder. This requires knowledge of the wind direction, water current, current speed of the boat, current direction of the boat, and the desired direction.

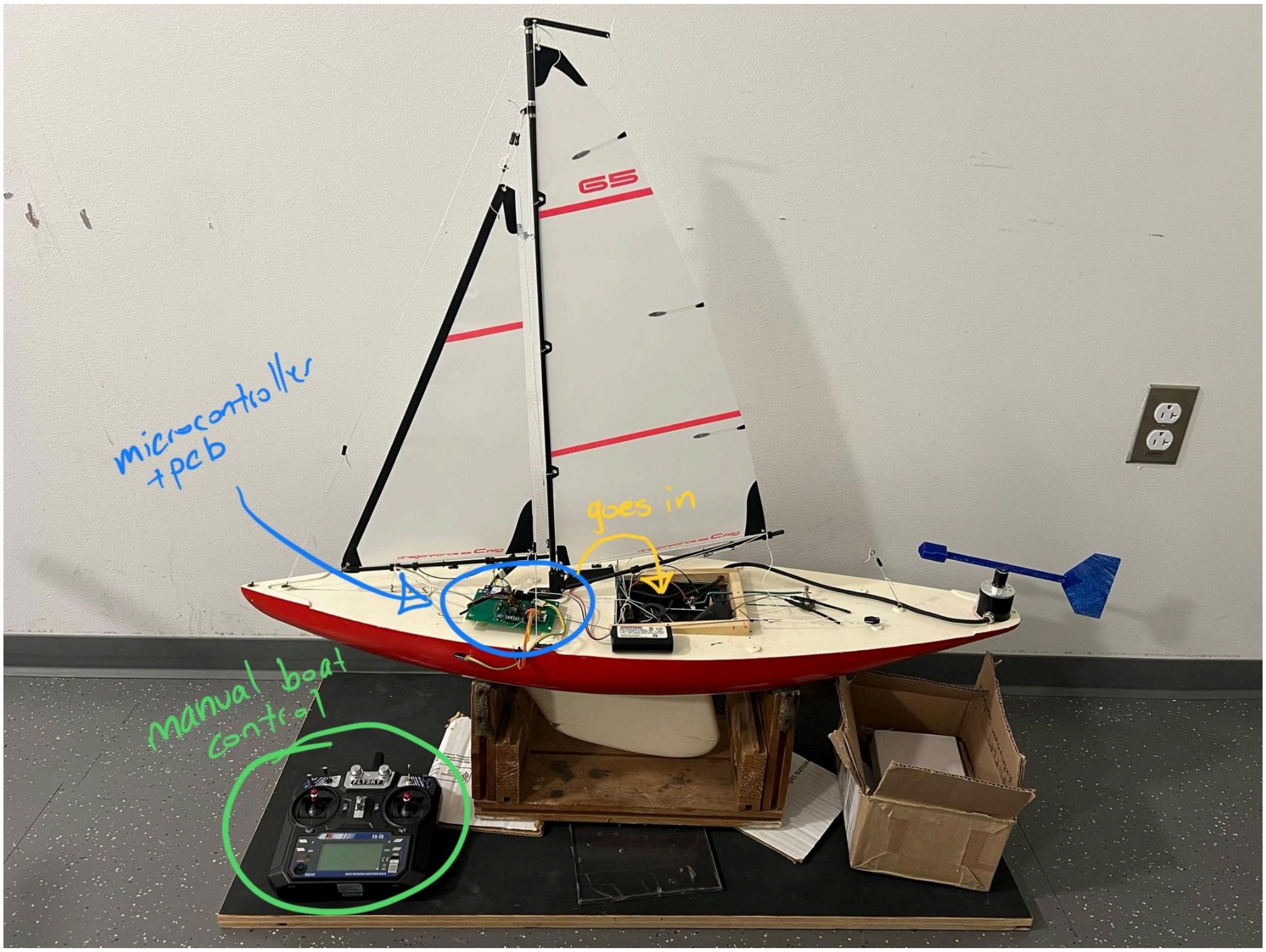
Given these factors, a boat should be able to direct itself towards a destination along a desired path.

1.2 Solution:

Working off of the base provided to us by the professor and the Spring 2022 group, we have a boat, which is capable of navigating calm water. It has a mast and rudder, which can be controlled with the provided motors. We also have a base of code, which translates external stimuli, such as the wind speed, direction, and current location, into the correct positioning of the mast and rudder for such movement. In our iteration of this project, we will use additional speed data to enhance the autonomous navigation features, and provide numerous real world tests of the autonomous navigation working. We also aim to introduce ease of life features like battery indicators, simpler charging / batteries, and an autonomous return to user mode.

Additionally, we will need to redesign a new PCB to accommodate new functionality, such as the speedometer and battery charging capabilities. We will be able to iterate on both the PCB and code libraries using the resources already available to us from the previous semester work, rather than starting from the ground up. Our main focus will be on streamlining the software side of the project, and optimizing our systems to work best in a physical environment.

1.3 Visual Aid:



1.4 High Level Requirements:

Our main priority is to review, improve and prove not just the existing autonomous capabilities of the sailboat, but also to implement new features and introduce novel hardware components to aid in the usage of the boat. To have a successful project, we have defined three goals which we aim to achieve:

1. The sailboat is successfully able to autonomously maintain a course along a body of water. With the ideal wind conditions, the boat will travel in a straight line with corrections within ±4° of its desired, or ideal, angle of travel.
2. The microcontroller in the PCB is able to effectively manipulate inputted telemetric data to follow a path defined by GPS coordinates on an open body of water with accuracy of

±3m, calculate the ideal mast and rudder position given a desired direction, compass reading, GPS location, boat speed and wind direction and battery level. We will be updating all of these values every 10s. Using telemetric systems, it sends travel data wirelessly to a receiving computer, which reads the real time location of the boat and other sensor data transmitted from the boat.

3. The remote controller is able to successfully aid in tasks including switching between a manual-control mode and an autonomous-control mode. The manual-control mode is controlled by the remote controller, so quick and accurate data is being sent from the remote to the boat. The remote controller also aids in abandoning the boat's current course, or direction of travel, and returns it to a predefined "home base" whenever called.

2. Design

2.1 Block Diagram

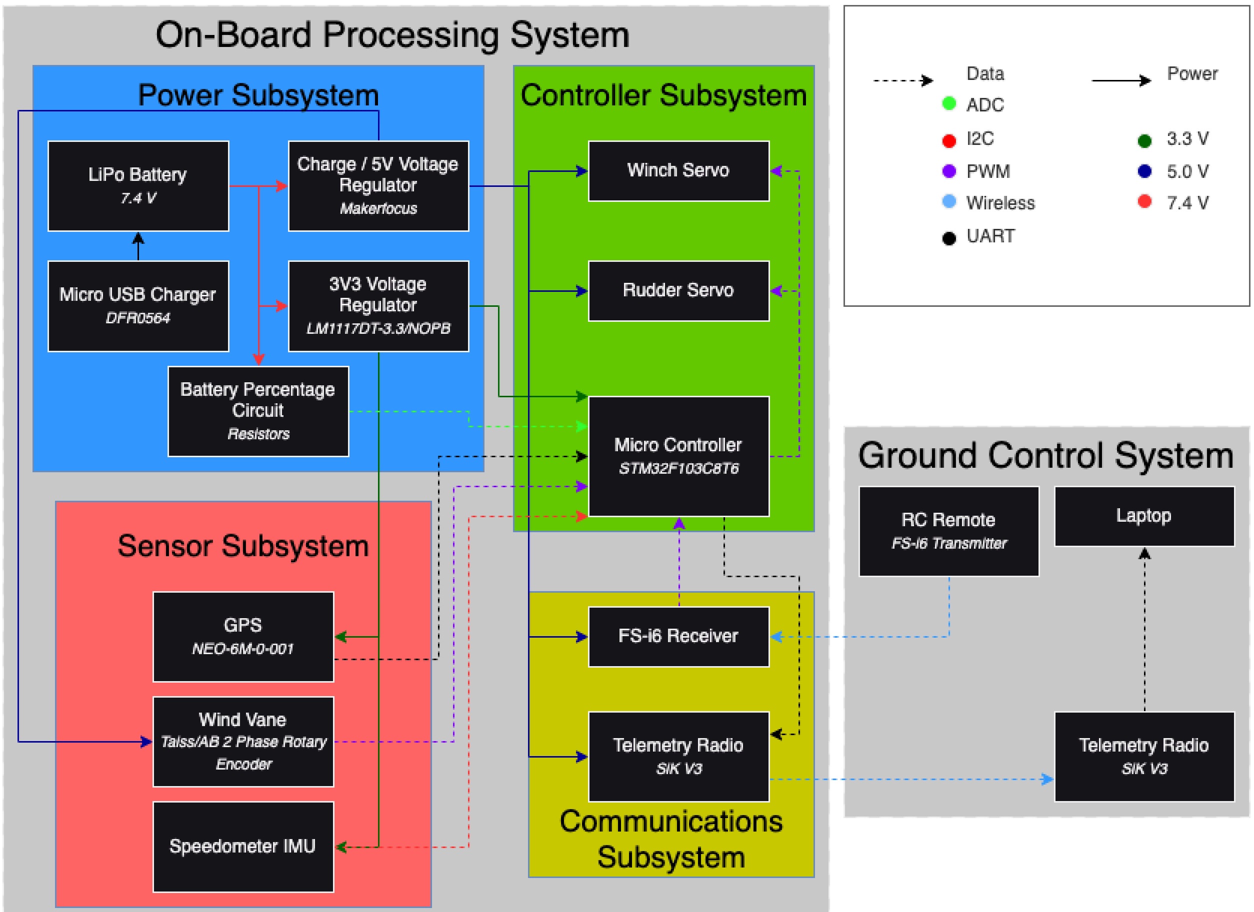


Fig 2.1.1 Block Diagram

2.2 Physical Design

2.2.1 Electronic System Waterproofing

To account for the sailboat's aquatic environment of operation, there has to be sufficient waterproofing to protect the cavity in the sailboat where the electronics will be located. In order to ensure the safety of our equipment, we plan on 3D printing a latch to be added atop the cavity. The latch will be waterproofed along its edges, and will also be waterproofed at its base on the boat, to guarantee that no water will be able to pass through. As shown in the Figure 2.2.1 below, the latch will have a routing tunnel that connects to an opening that can be sealed with a twist on seal. The routing tunnel prevents the cable from getting lost in the cavity which will result in an effort to fish it out. This approach requires the electronic parts to be steadily taped into the boat so that its movement will not cause the loss of the cables. This latch design aims to achieve secure waterproofing while maintaining ease of use through simply opening the twist on seal.

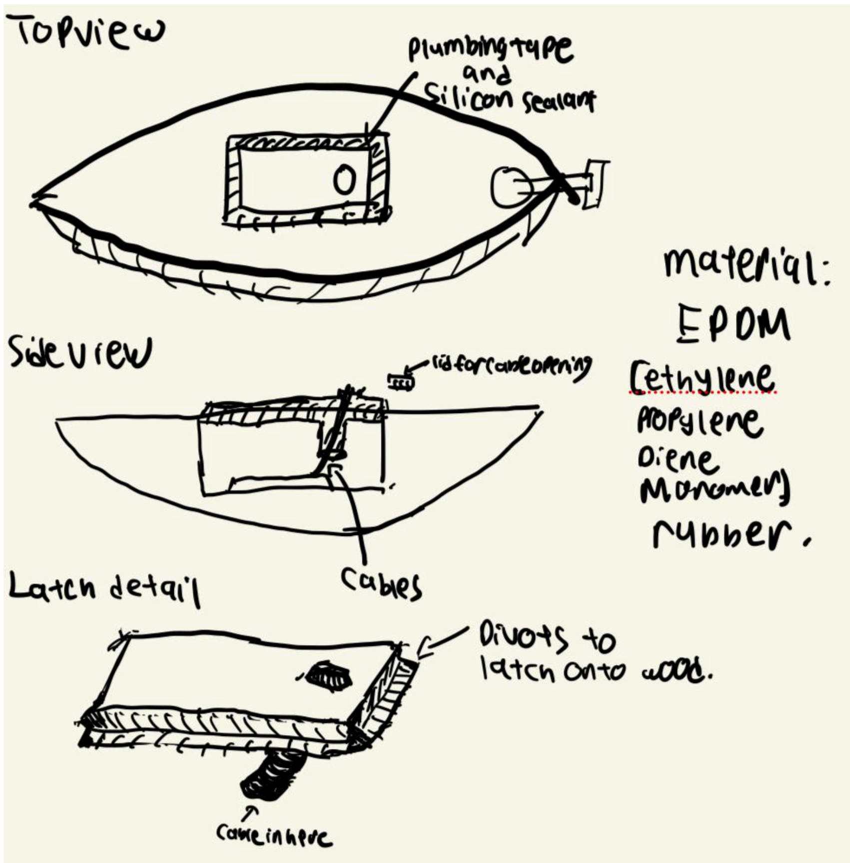


Fig 2.2.1 3D Printed Waterproof Latch.

2.3 Autonomous Steering Algorithms

2.3.1 Sail Winch Control

The sail winch angle is controlled based on the apparent wind angle measured by the wind vane encoder and the measured heeling angle of the boat is. Depending on the heeling angle, there are two states the sail winch control program is in which are the “Safe State” and “Dangerous State”. As detailed in Fig 2.3.1, when the absolute value of the heeling angle is > 15 degrees, the control is moved to the “Danger State”, whereas when the heeling angle is < 15 degrees, the control moves to “Safe State”. What the Sail Winch Control program is different for each state

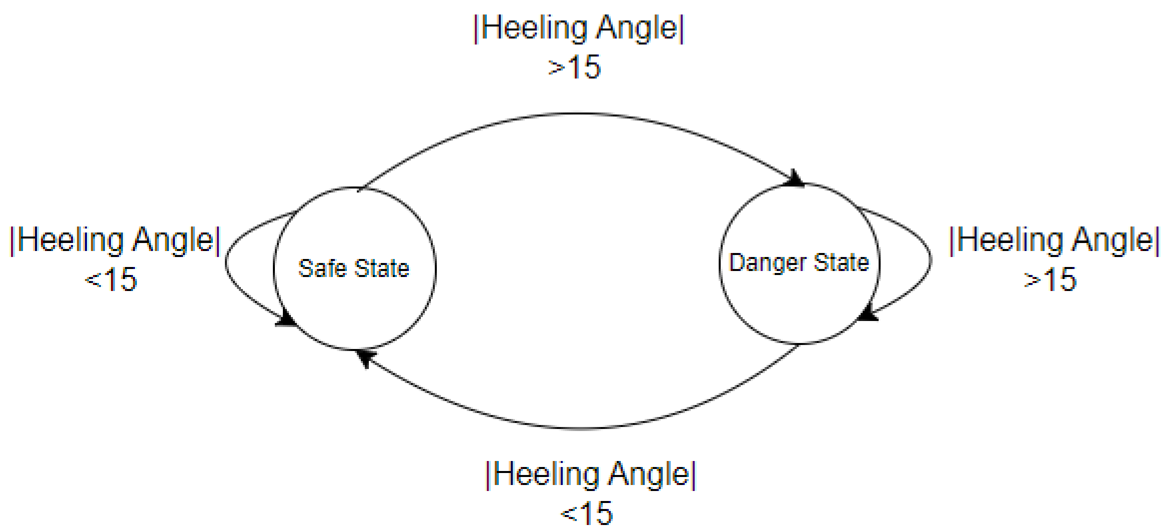


Fig 2.3.1.1 Sail Winch Control State Diagram

2.3.1.a Safe State Operation:

When operating in the safe state the sail chord angle determined by the sail winch servo is set based on the value in the lookup table of optimum values in Table 2.3.1.1 corresponding to the Apparent Wind Angle obtained by the wind vane encoder.

Table 2.3.1.1: Optimal Sail Chord Angle for Different Wind Angles

Apparent Wind Angle	Point of Sail	Sail Angle
$0 \leq \theta \leq 45 \| 315 \leq \theta \leq 360$	No-Go Zone	0°
$45 \leq \theta \leq 75$	Close-Hauled	15°
$75 \leq \theta \leq 105$	Beam Reach	-45°
$105 \leq \theta \leq 135$	Broad Reach	-60°

$135 \leq \theta \leq 225$	Running	±90°
$225 \leq \theta \leq 255$	Broad-Reach	60°
$255 \leq \theta \leq 285$	Beam Reach	45°
$285 \leq \theta \leq 315$	Close-Hauled	15°

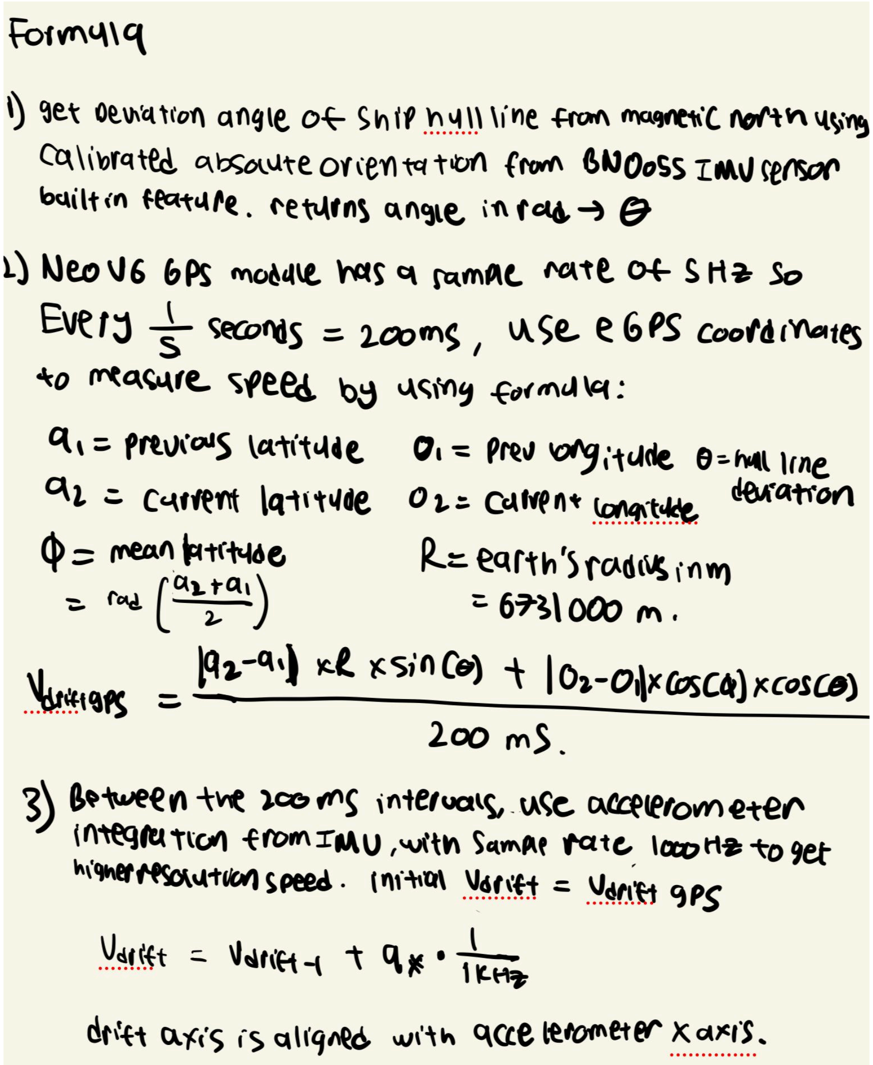
2.3.1.b Danger State Operation:

When operating in the Danger State, we want to recover the absolute heeling angle to <15 degrees as fast as possible. This can be done by reducing the heeling force caused by the wind by “letting out sails” which means increasing the sail chord angle which decreases the angle of attack in regards to the wind. We leave this state when the boat is no longer in an absolute heeling angle of > 15 degrees .

2.3.2 Drift Velocity Measurement

To calculate drift velocity with good resolution and accuracy, a multiple sensor approach is used. The BNO055 IMU allows us to measure acceleration with a sample rate of 1000Hz. Through acceleration integration we could get a change in velocity. However, this value is prone to sensor drift if continuously compounded, this integration also requires an initial velocity to accurately represent the drift velocity.

As a solution to this, we utilize the NEO6M-V6 GPS’ coordinate data and the absolute orientation measurement from the BN0055 IMU to re-calibrate the velocity every 200ms. This interval is due to the 5hz sample rate of the GPS sensor. The algorithm below shows how data from these sensors will be utilized to get drift velocity.



Formula

1) get Deviation angle of Ship hull line from magnetic north using calibrated absolute orientation from BNO055 IMU sensor built in feature. returns angle in rad → θ

2) Neo V6 GPS module has a sample rate of 5Hz so Every $\frac{1}{5}$ seconds = 200ms, use e GPS coordinates to measure speed by using formula:

a_1 = previous latitude $\quad$ O_1 = prev longitude $\quad$ θ = hull line deviation

a_2 = current latitude $\quad$ O_2 = current longitude

ϕ = mean latitude $= \text{rad}\left(\frac{a_2+a_1}{2}\right)$ $\quad$ R = earth's radius in m = 6731000 m.

$$V_{drift\,gps} = \frac{|a_2-a_1| \times R \times \sin(\theta) + |O_2-O_1| \times \cos(\phi) \times \cos(\theta)}{200\ \text{ms}}.$$

3) Between the 200ms intervals, use accelerometer integration from IMU, with sample rate 1000Hz to get higher resolution speed. Initial $V_{drift} = V_{drift\ gps}$

$$V_{drift} = V_{drift-1} + a_x \cdot \frac{1}{1\text{KHz}}$$

drift axis is aligned with accelerometer x axis.

Fig 2.3.2.1 Drift Velocity Derivation Formula

2.3.3 Rudder Control

The rudder is controlled using a PI controller that takes a hyperparameter weighted sum of deviation angle and boat sideways drift speed as an input. Both of these values need to be counteracted by an appropriate rudder angle so the output of the PI controller is a rudder angle. The operation of this control system can be seen below in Fig 2.3.3.1.

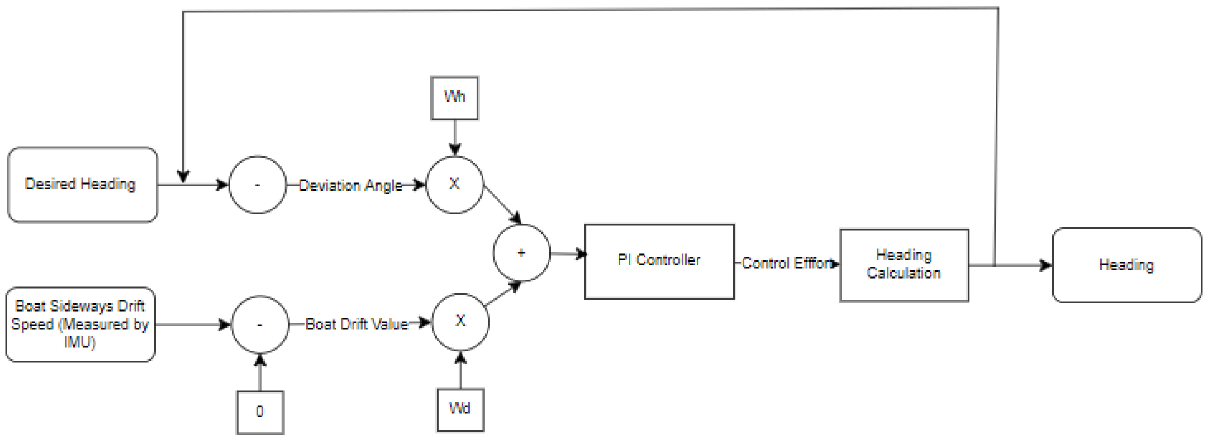


Fig 2.3.3.1: Block Diagram for Rudder Control System

2.3.4 Low Battery Autonomous Mode Activation

Upon reading a moving average (to account for jumping values as the battery drains) of 30% on the battery, the boat will enter an autonomous mode, directing the boat back to the starting point, regardless of its intended path of travel. This mode can be exited to manual mode control, but if changed back to autonomous path sailing will only change back to autonomous return.

2.4 Functional Overview & Block Diagram Requirements

2.4.1 Controller Subsystem

The Sailboat Control Subsystem serves as the central mechanism for both autonomous and manual sailboat operation, orchestrating essential functions for movement and functionality.

In autonomous mode, it takes data from sensors from the sensor subsystem like the GPS, WindVane, and speedometer IMU and adjusts the sail and rudder servos to optimal angles based on these measurements. These sensor measurements are also processed and reported. The IMU (**BNO055**) sends data through an I2C bus, this data will be used by the microcontroller to measure how far deviated the sailboat's course is in relation to the destination compass heading. This data in the autonomous steering algorithm Fig 2.4.1.1 to determine when and how the sail and rudder angles should be adjusted. The GPS sends data via UART, this data will be used to track the boat and its progress towards its destination waypoint. The wind vane encoder and the speedometer IMU both send data to the microcontroller through PWM signals. The data from the wind vane encoder is used to determine the apparent wind angle which will be used to determine the sail angle and rudder angle based on the autonomous control algorithm which is detailed in the flowchart. The data from the Speedometer IMU is processed to estimate the speed of the boat in different directions which will be used as feedback to keep the boat in its course direction, the detailed actions based on its feedback can be viewed in flowchart Fig 2.4.1.1.

All these sensor readings will then be sent to the ground control system via Telemetry radio in the communication subsystem. The microcontroller sends this data to the radio via UART and the Telemetry radio uses 915 Hz wireless communication with the other Telemetry radio in the ground control system to report the sensor data. This sensor data can be viewed in the laptop from the ground control system and is essential for debugging, verification, determining hyperparameters, and monitoring the performance of the boat.

This microcontroller-driven system ensures precise sail adjustments to trim sails, optimize speed, maintain compass heading, and navigate to destinations. The microcontroller adjusts the rudder and sail servo angles using a PWM signal which will instruct it to move to the desired angle.

Manual mode operation involves wireless communication with the FS-I6 Transmitter remote from the Ground Control System for real-time adjustments. The transmitter has 6-channels and delivers instructions through wireless connection to the FS-I6 Receiver in the Communication subsystem. The receiver then delegates this data via PWM to the microcontroller. When the joystick channels are changed, the microcontroller will send a PWM to the appropriate servo to adjust their angle. 2 out of 6 of the channels are for special capabilities which are to turn the autonomous mode ON or OFF, and to call the return to base function. When the microcontroller receives this signal from the receiver, it takes action according to the request.

All the components of the controller subsystem are powered by the Li-Ion battery in the power subsystem. To supply the microcontroller with 3.3V, the battery is wired to a 3.3V voltage regulator. To supply the rudder and winch servo with 5V, the battery is wired to a 5V voltage regulator.

To ensure that the Controller Subsystem is fulfilling its responsibilities for receiving transmissions from the remote, taking data from the sensor subsystem, and adjusting the servo angles, a requirements & verification table can be found below. Note that some of the verification tests are done in an outdoor setting.

Table 2.4.1: Controller Subsystem Requirements and Verification.

Requirements	Verification
• The controller subsystem must not allow rudder and sail servo to move in response to the RC remote when in autonomous mode	• Place the sailboat on the lazy susan and turn off the box fan so that the wind vane encoder don't pick up any wind angle • Turn on the sailboat, wait 5 seconds, and turn the autonomous switch to ON. • Move the two joysticks from manual mode and confirm that the servos are not moving
• The controller subsystem should send accurate sensor data through telemetry radio to the laptop in ground control subsystem	• Turn on the laptop with the data viewer • Place the sailboat on the lazy susan and set it to autonomous mode • Turn on the box fan from any angle that is not in the No-Go zone. • The data viewer in the laptop should report values the AWA, compass heading, current GPS measurement, servo angles, speed estimation, and battery percentage estimate.
• The controller subsystem should be able to send PWM signals to the rudder and sail servo and move it to its desired angle with a tolerance of maximum error of 2°	• Place the boat in the lazy susan and add cardboards below the platform so the lazy susan doesn't rotate. • Calibrate the sail servo and rudder servo to be aligned with the 0 degree start position(Aligned with the hull centerline) • Run a custom program that sets the sail

	servo angle and rudder angle to a specific predetermined angle ● Use a protractor to measure the actual angles of the rudder and sail servo as they respond to the PWM signals ● Verify that the actual angles fall within tolerance of ±2° of the desired angles
● The controller subsystem should correctly adjust the sail and rudder angle according to the apparent wind angle based on the lookup table specified in Table 2.4.1.1 to a maximum error of 2°	● Place the boat in the lazy susan such that its heading is aligned with 0 degrees ● Place a box fan directly in front of the lazy susan. ● Calibrate the sail servo and rudder servo to be aligned with the 0 degree start position(Aligned with the hull centerline) ● Turn the boat to Autonomous mode on through the remote control ● For each desired apparent wind angle to be tested based on Table 2.4.1.1, rotate the sailboat such that its heading aligns with the desired angle. ● Allow the boat's autonomous steering algorithm to adjust the rudder and sail servo angles ● Use a protractor to measure the actual angles of the rudder and sail servo as they respond to the PWM signals ● Repeat for each of the different experimental angles ● Verify that all the actual angles fall within tolerance of ±2° of the desired angles

● The controller subsystem should be able to adjust rudder angle based on the deviation of the current compass angle and the destination compass heading. This adjustment should put the boat back on acceptable deviation range of <=4° in less than 10 seconds	● Place the boat in a small water bath(ex. Inflatable kid pool) ● Set the boat to Autonomous mode and set a imaginary heading straight forward from the starting position of the boat ● Point a box fan to blow from any angle that is not in the No-Go zone [Table 2.4.1.1] ● Allow the boat to sail autonomously ● View the data logged in the laptop and watch for the moments when the heading deviation is >=4 degrees and measure how long it took to return to a heading less than that
● The controller subsystem should be able to perform rudder angle adjustments when the speedometer IMU detects a sideways drift speed of >2m/s. This adjustment should counteract the sideways drift and bring it back to an acceptable range of <2m/s	● Place the boat in a small water bath(ex. Inflatable kid pool) ● Set the boat to Autonomous mode and set a imaginary heading straight forward from the starting position of the boat ● Point a box fan to blow from any angle that is not in the No-Go zone [Table 2.4.1.1] ● Allow the boat to sail autonomously ● View the data logged in the laptop and watch for the moments when the speedometer measurement is >2m/s and measure how long it took to return to a value less than that
● The controller subsystem must be able to reach its destined waypoint with an error range of 5m	● Place the boat in a outdoor water environment ● Mark a destination waypoint around 20m away from the boat but in hands reach from shore with an anchored float. ● Set the boat to Autonomous mode and set a destination waypoint to the marked destination coordinates ● Allow the boat to sail autonomously until it reaches it completes its journey ● Record its ending location with another weighted float.

	• Measure the distance between the two float markers to derive its error • Confirm error is below 5m
• The controller subsystem 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.
• The controller subsystem should move the servos in response to the RC wireless controller with latency of <25ms	• Place the sailboat on the lazy susan • Turn on the sailboat, wait 5 seconds, and make sure the autonomous mode is OFF. • Move a joystick from the RC controller • Use the data logging capability to measure the difference between the timestamps of wireless controller input and servo movement and analyze the difference • Confirm it is <25ms
• The controller subsystem should be able to keep the heeling angle of the sailboat to <|15| degrees to prevent capsizing	• Place the boat in a small water bath(ex. Inflatable kid pool) • Set the boat to Autonomous mode and set a imaginary heading straight forward from the starting position of the boat • Point a box fan to blow from any angle that is not in the No-Go zone [Table 2.4.1.1] • Allow the boat to sail autonomously • Manually agitate the sailboat to have a heeling angle > 15 degrees. Confirm it is >15 degrees by simultaneously viewing the data in the laptop. • Observe the response of increasing sail winch angle and see if it could recover its heeling angle to <15 degrees

2.4.2 Sensor Subsystem

The Sensor subsystem serves as the backbone of the autonomous functionality of this sailboat. In autonomous mode, the sensors feed data to the microcontroller in the controller subsystem with its appropriate signals.

The IMU(**BNO055**) is used to measure the current compass heading of the boat in relation to the destination's compass heading which is calibrated as the "dead-north" of the compass when we set the destination through the ground control system. This measurement is sent to the microcontroller through an I2C bus and will be used in the steering algorithm.

The GPS (**NEO-6G**) will keep track of the boat's position. It will send position data to the microcontroller which will be used to implement a "return back home" feature which would enable the boat to autonomously navigate back to its starting position. functionality. The GPS also determines the heading through comparing its current location to its previous location the last time it was updated. The heading from the GPS is extremely inaccurate when the boat is not traveling 5 m between updates. This data will be sent to the microcontroller via UART to the microcontroller.

The Wind Vane (**MA3 Miniature Absolute Magnetic Shaft Encoder**) will inform the microcontroller of the apparent wind angle which is central to the calculations for steering the boat appropriately by adjusting sail and rudder angles. The data is sent to the microcontroller through a PWM signal.

The IMU is also a valuable tool for optimizing sail trim and as a feedback tool for the steering algorithm. We can estimate the maximum speed the sailboat is likely to attain using the formula for the maximum speed of a displacement hull moving through water. This speed is limited by the speed of a wave whose length is equal to the length along the waterline (LWL) of the hull. The formula for maximum hull speed is:

$$HS(\mathrm{m/s}) = 0.7\sqrt{\mathrm{LWL\ (ft)}} \approx 1$$

as the waterline length of the boat is approximately 1 ft or a bit more. This estimated speed is calculated by the microcontroller. The IMU sends data on the acceleration and orientation which will be processed into an estimated speed this is done through basic integration of the acceleration in its appropriate axis.

All the components of the controller subsystem are powered by the Li-Ion battery in the power subsystem. To supply the IMU and GPS with the required 3.3V the battery is wired to a 3.3V voltage regulator. To supply the Windvane Encoder with the required 5V the battery is wired to a 5V voltage regulator.

To ensure that the Sensor Subsystem is fulfilling its responsibilities for measuring the appropriate data, sending data to the controller subsystem with good latency, and staying live throughout the boat's operation a requirements & verification table can be found below:

Table 2.4.2 Sensor Subsystem Requirements and Verification

Requirement	Verification
• The IMU should be able to monitor the current heading of the boat to a tolerance of ±5°.	• Place lazy susan above a paper with different angles marked on it • Place the boat on top of lazy susan • Align the boat to a known compass heading of 0 degrees. • Turn on the IMU and record its reading. • Gradually rotate the boat in increments, noting the corresponding compass readings. • Compare the compass readings with the known headings, ensuring they fall within the tolerance of ±5°.
• The GPS should be capable of reporting boat coordinates with an accuracy of ±2.5 meters.	• Bring the boat into a room with 4 corners and dimensions >=9 meters on each edge. • Start by bringing the boat to one corner of the room • Measure the coordinates at that location. • Move to each of the other corners of the room and record the coordinates by the GPS at each of these corners • Calculate the accuracy of these GPS recordings compared to the supposed theoretical value based

	on the known dimensions of the room.
• The Windvane encoder data should allow the appropriate algorithm to measure the direction of wind within a tolerance of ±5°. Anything greater than this will cause errors in adjusting sail chord angle which may exacerbate the error between course sailed and compass heading.	• Place the boat in the lazy susan such that its heading is aligned with 0 degrees • Place a box fan directly in front of the lazy susan. • Calibrate the wind vane encoder For each desired apparent wind angle to be tested based on Table 2.4.1.1, rotate the sailboat such that its heading aligns with the desired angle. • For each wind angle, check the laptop for the measured apparent wind angle by the wind vane encoder • Verify that all the actual angles fall within the measurement tolerance of ±5° of the desired angles
• The IMU should be able to allow the algorithm to estimate the speed of the boat to an accuracy of 0.5m/s or 5% of true velocity	• Place the boat in the lazy susan • Place the lazy susan in a stationary treadmill, where the hull centerline is perpendicular with the axis of the treadmill belt. • Turn the treadmill on and move it at a safe speed of 1.5m/s • See the recording and estimated speed value calculated by the IMU • Verify that is an accuracy of 0.5m/s or 5% of true velocity of 1.5 m/s

2.4.3 Power Subsystem

The sailboat's power management system is designed around a 7.4V Li-Ion battery, serving as the primary power source for the entire system. This battery is connected to both a 3.3V and 5V voltage regulator, ensuring stable power distribution to the Control, Sensor, and Communication Subsystems. The 5V Voltage Regulator, a Makerfocus component, provides a consistent power supply to essential components such as the Winch Servo, Rudder Servo, Wind Vane Encoder, Telemetry Radio, and Receivers. Likewise, the 3.3V Voltage Regulator, utilizing the LM1117DT-3.3/NOPB, delivers steady power to critical components like the Microcontroller, IMU, and GPS.

A USB charging unit (**DFR0564**) facilitates convenient battery charging, enhancing the overall usability of the power system setup. This board is soldered onto the board itself, and when set to charging mode, can charge the battery. The micro USB port will always have a wire attached to it, which can be removed from the interior of the boat for easy charging without having to move or remove any other components from the interior. This can be plugged into any USB port or portable power bank, as long as it can provide 3-6 Volts (5V ideal) and 1 Amp. The USB cable can be kept inside of the boat when not in use, improving the waterproof capability by leaving no open ports that water can get into while the boat is in operation.

Additionally on the board, there's a STDP switch that protects the circuit while the battery charges, or the circuit is not being used. When on charging mode, the battery is only connected to the charging circuit, leaving the board protected from any jumps in voltage or current. This also reduces the amount of work needed to charge, as the battery can stay permanently attached to the board instead of removing it to charge, or moving the battery to another location on the PCB. Then, there's another option on the switch to connect the battery to the board, powering all the functions normally expected. It can also be turned off, keeping power from anything on the board, and preserving the life of the battery.

The battery level indication requires the circuit shown in Fig 2.4.3.1 [1]. As the Li-Ion battery uses its charge to power the circuit, it will gradually decrease in voltage from 7.4V down to 6.4V. The difference in voltage can be easily measured using an ADC pin from the STM chip. To get the voltage down to a safe readable level, 3 resistors can be used to reduce the voltage down by ⅓ its original value. This will ensure that at its maximum, the voltage going into the chip will be less than 3.3V. In order to reduce the current draw from the battery, we will choose 3 100 kOhm resistors. When connected to the 7.4V battery, they will draw 24.7 microAmps of power.

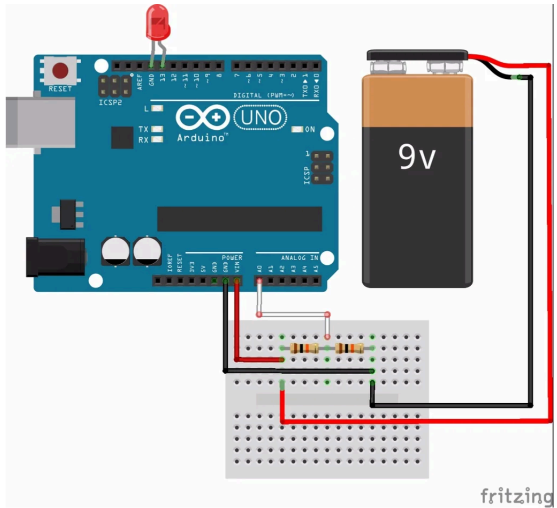


Fig 2.4.3.1 Battery Indicator Circuit

Using a simple equation, we can calculate the battery percentage through a reading made on the board:

$$\text{Voltage} = 7.4(ADC_{val} \times \frac{3}{4095})$$

Where the ADC_value is read in through the 3rd resistor in the circuit, 3 is a multiplier for accounting for the ⅓ voltage division at that point, 4095 is a maximum voltage reading from the STM32 chip, and 7.4 is the theoretical maximum voltage of the battery.

This data can be processed on the microcontroller, and sent to a receiving computer along with the other data. See section 2.4.1 and 2.4.4 on data transmission. When the battery reaches 30%, we want the boat to begin to return back to the waypoint autonomously.

The power subsystem is built for water conditions through insulation and waterproofing measures, safeguarding against intrusive water and electrical short circuits common in marine environments. These measures ensure the system's safety and resilience in regards to the sailboat operation, making it reliable under exposure to splashes and spray.

To ensure that the Power Subsystem is fulfilling its responsibilities for supplying constant power when at healthy battery conditions, not short circuiting in water conditions, and successful charging capabilities a requirements & verification table can be found below.

Table 2.4.3 Power Subsystem Requirements and Verification

Requirements	Verification
• Must be able regulate battery voltage to power components throughout the discharge cycle of the battery and automatically cutting out power when battery voltage drops too low	• Connect the input of the voltage regulator to the battery supply. • Connect the output of the voltage regulator to a programmable load. • Set the voltage supply to the maximum battery voltage (e.g. 7.4V for a Li-Ion battery). • Measure the output voltage of the voltage regulator using a multimeter under both no-load and full-load conditions. • Ensure that the output voltage remains within the specified range (e.g., 3.3V ±5%) at all times. • Gradually lower the input voltage from the battery to simulate decreasing battery levels. • Verify that the output voltage of the voltage regulator remains stable until the battery voltage reaches a predefined threshold • Once the battery voltage drops below the threshold, confirm that the voltage regulator cuts off power, resulting in a decrease in the output voltage to 0V or near 0V. • Confirm that the voltage regulator maintains power cutoff to prevent over-discharge of the battery, ensuring the protection of the battery and connected components.
• The battery must be able to be recharged via the micro USB connector within 6 hours.	• Begin with the battery completely discharged. • Plug the micro USB into the charging port. • Initiate a timer to track the charging duration. • Regularly check the battery's charging status and voltage using appropriate tools. • Note the time when the battery reaches full charge.

	● Calculate the elapsed time from the start of charging to full charge and compare it to the 6 hour target
● The battery should be able to last minimum of 3 hours from a full charge when boat is used for testing	● Begin with the battery completely charged ● Use the boat to test, verify, and debug other aspects of the requirements ● Ensure the boat is still on at the end of session. ● If single session is >3 hours the verification is successful ● Otherwise keep adding total times that the boat is not off yet and the verification succeeds when total time is >3 hours
● The power subsystem should not short circuit under the conditions of water splashing and during boat use	● Expose the power subsystem to simulated water splashing conditions. ● Observe the system for any signs of electrical malfunction or short circuiting. ● Repeat the test multiple times to ensure consistency. Part 2 ● Run a program that oscillates the rudder servos in a relatively high frequency to simulate the worst case scenario of power consumption ● Monitor if there are any power malfunctions or short circuits.
● The battery percentage read by the circuit should be accurate within 5% of the battery charge	● Connect a fully charged Battery supply to a programmable load(e.g. potentiometer) ● Measure the output voltage of this with a multimeter under no load and full load conditions. ● Plug the battery into the board and compare the calculated value using the voltage with the value read by the microcontroller.

2.4.4 Communication Subsystem

The communication subsystem serves as the link between the sailboat and the Ground Control Subsystem, facilitating the exchange of data.

The Telemetry Radio using the SiK V3 technology, is used to transmit various data types, including servo positions, sensor readings, boat position, battery percentage, and microcontroller calculations, to the Ground Control Subsystem. Operating at a frequency of 915MHz, it should ensure efficient data transfer with minimal loss or errors, which is required for reliable communication.

The FS-I6 Receiver is used during manual mode operation, receives user control inputs from the FS-I6 RC remote transmitter and forwards them wirelessly to the microcontroller for servo control. Additionally, it receives signals indicating the activation of autonomous mode (e.g. low battery) or the "return to base" command, initiating the corresponding actions. It operates at 2.4GHz and has six channels. The details on these channels can be found in table 2.4.4.1

Table 2.4.4.1: FS-I6 Controller Channel Mapping

Channel	Remote	Mapping	Use
1	Right Gimbal ←, →	Winch Servo	←: Tighten Sail →: Loosen Sail
2	Right Gimbal ↑, ↓	N/A	N/A
3	Left Gimbal ↑, ↓	Rudder Servo	↑: Rudder → Starboard ↓: Rudder → Port side
4	Left Gimbal ←, →	N/A	N/A
5	SwC	Sailing Mode	1: Manual 2: Autonomous 3: Return to Base
6	SwD	Set Base Position	1 → 2: Sets Base Position to Current GPS Location

The communication subsystem is powered by the power subsystem. Both the receiver and the telemetry radio requires 5V to run so it takes input from the 5V regulator of the power system

To ensure that the Communication Subsystem is fulfilling its responsibilities for communicating the transmitter signals and sending correct data through the telemetry radio a requirements & verification table can be found below.

Table 2.4.4.2 Communications Subsystem Requirements and Verification

Requirements	Verification
• The data from the microcontroller has to be properly transmitted with latency of less than 60 ms through the telemetry radio	• Configure the microcontroller to send a series of data packets at regular intervals through the telemetry radio. • Set up the laptop to record the timestamps of incoming data packets as they are received from the telemetry radio. • Calculate the latency for each received data packet by subtracting the timestamp in the packet from the current time when the packet is received. • Verify that it is <60ms
• Turning on the autonomous functionality should not be able to be turned on before 5s after the remote is turned on. To ensure sensors calibrate.	• Place the boat on lazy susan and turn it on • Place box fan on an angle that is not in the No-Go zone of the sailboat[Table 2.4.1.1] • Turn on the RC remote and immediately try to turn on autonomous mode. • The boat should not move any of its servos indicating that autonomous mode was not turned on

2.4.5 Ground Control Subsystem

The Ground Control Subsystem serves as the interface for manual control of the sailboat, activation of the "return to base" function, and data tracking from the onboard systems. The FS-16 Transmitter, operating at a frequency of 2.4GHz and equipped with six channels, is what allows for wireless transmission of user commands from the remote control to the onboard processing system during manual mode operation. Additionally, it sends signals to activate or deactivate autonomous mode, triggers the "return to base" command, and sets base position.

The Telemetry Radio Receiver is used to receive data transmitted from the Telemetry Radio Transmitter onboard the sailboat. Through a UART connection, it communicates with a laptop, facilitating the transfer of data for real-time monitoring and analysis. This receiver acts as a bridge between the onboard systems and the ground control station, enabling seamless communication and data tracking of servo, sensor, position, and microcontroller calculations.

To ensure that the Ground Control Subsystem is fulfilling its responsibilities for communicating the transmitter signals and receiving correct data through the telemetry radio a requirements & verification table can be found below.

Table 2.4.5 Ground Control Subsystem Requirements and Verification

Requirements	
• The FS-I6 transmitter should transmit signals to the appropriate channel to move the appropriate servo in manual mode. Refer to table 2.4.4.1	• Place the boat in stationary lazy susan • Turn the boat on in Manual mode • Move the right gimbal left and right and verify that it is the sail servo rotating • Move the left gimbal up and down and verify that it is the rudder servo moving
• Laptop should be able to view data from telemetry radio.	• Turn on the sailboat and run the monitoring program in the laptop • See if the data changes as the different sensors are moved.

2.4 Tolerance Analysis

2.4.1 Heading Tolerance Analysis

Ensuring that the sailboat is able to autonomously travel at a steady heading is our primary goal. To do this, we are targeting that deviation $\theta \leq 9°$ at all times. In order to do this, the following list of assumptions were made:

1. Waves and other water turbulence (such as fluid friction) are ignored
2. The magnitude of the lift force on the sail remains near-constant
3. The magnitude of the force on the rudder remain near-constant
4. The roll and pitch angles are 0°
5. The yaw angle variation does not affect forces
6. The center of gravity *G* of the sailboat does not change

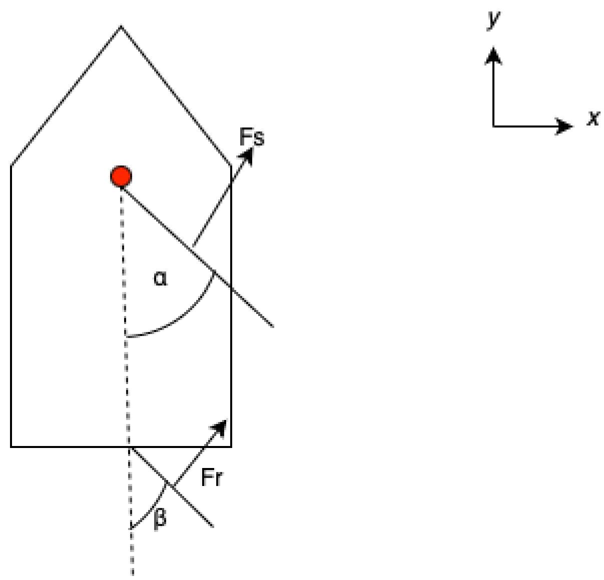


Figure 3: Free Body Diagram of Sailboat

In Figure 3, F_s and F_r are the forces on the sail and rudder respectively, α is the sail angle and β is the rudder angle. Using this diagram, we can come up with systems of equations relating all four of the aforementioned quantities using variations of Newton's Second Law $F = ma$.

Since acceleration is the double derivative of displacement in a certain direction, we can rewrite it as $a = \frac{d^2x}{dt^2}$. Furthermore, we will define another angle ϕ to be the angle of the compass heading: $\phi = (\text{Compass Heading})_{\text{init}} - \text{Compass Heading})_{\text{actual}}$.

We are also using certain variables related to the center of gravity:

- x_{gs} is the *x*-distance between the boat's center of mass and the point of application for F_s
- y_{gs} is the y-distance between the boat's center of mass and the point of application for F_s
- x_{gr} is the *x*-distance between the boat's center of mass and the point of application for F_r
- y_{gr} is the *y*-distance between the boat's center of mass and the point of application for F_r

If $\alpha > 0, \beta > 0$:

1. $x := F_s|\sin\alpha| - F_r|\sin\beta| = m\frac{d^2x}{dt^2}$
2. $y := F_s|\cos\alpha| - F_r|\cos\beta| = m\frac{d^2y}{dt^2}$
3. $F_s|\sin\alpha|y_{gs} - F_r|\sin\beta|y_{gr} + F_s|\cos\alpha|x_{gs} - F_r|\cos\beta|x_{gr} = m\frac{d^2\phi}{dt^2}$

If $\alpha < 0, \beta > 0$:

4. $x := F_s|\sin\alpha| - F_r|\sin\beta| = m\frac{d^2x}{dt^2}$
5. $y := -F_s|\cos\alpha| - F_r|\cos\beta| = m\frac{d^2y}{dt^2}$
6. $-F_s|\sin\alpha|y_{gs} - F_r|\sin\beta|y_{gr} - F_s|\cos\alpha|x_{gs} - F_r|\cos\beta|x_{gr} = m\frac{d^2\phi}{dt^2}$

If $\alpha < 0, \beta < 0$:

7. $x := F_s|\sin\alpha| - F_r|\sin\beta| = m\frac{d^2x}{dt^2}$
8. $y := -F_s|\cos\alpha| + F_r|\cos\beta| = m\frac{d^2y}{dt^2}$
9. $-F_s|\sin\alpha|y_{gs} + F_r|\sin\beta|y_{gr} - F_s|\cos\alpha|x_{gs} + F_r|\cos\beta|x_{gr} = m\frac{d^2\phi}{dt^2}$

If $\alpha > 0, \beta > 0$:

10. $x := F_s|\sin\alpha| - F_r|\sin\beta| = m\frac{d^2x}{dt^2}$
11. $y := F_s|\cos\alpha| + F_r|\cos\beta| = m\frac{d^2y}{dt^2}$

12. $F_s|\sin\alpha|y_{gs} + F_r|\sin\beta|y_{gr} + F_s|\cos\alpha|x_{gs} + F_r|\cos\beta|x_{gr} = m\frac{d^2\phi}{dt^2}$

We can also derive the following equations if we introduce three more variables: *l* being the distance between G and the rudder, *L* being the length of the sail and *r* being the length of the rudder:

13. $x_{gs} := \frac{L}{2}|\cos\alpha|$
14. $y_{gs} := \frac{L}{2}|\sin\alpha|$
15. $x_{gr} := l + \frac{r}{2}|\cos\beta|$
16. $x_{gs} := \frac{r}{2}|\sin\beta|$

Upon completing simulations, we figured that having $\phi = 4$ as a target would keep the sailboat within the desired target range.

2.4.2 Battery Life Analysis

To calculate the battery life of the selected battery, the current draw of our system has to be calculated and used in tandem with the capacity of the battery. To simplify calculations, we made the following list of assumptions:

1. Servos are on 80% of the time
2. The current is calculated on the absolute maximum values provided in the respective datasheets
3. The Li-Ion battery should only be used until 25% of battery capacity as this is where the output voltage deteriorates[16]

2.4.2.1 Current Draw

a) Controller Subsystem (Total = 892mA)
    i) Microcontroller (STM32F103C8)[13] → 150 mA total current into VDD power lines
    ii) Sail Winch Servo (Joysway 880545)[14]→ 0.15A no load * 0.2 + 0.4A working load *0.8 = 0.35A = 350mA

iii) Rudder Servo (Joysway 881504)[15]→ 0.16A no load * 0.2 + 0.45A working load *0.8 = 0.392A = 392mA

b) Sensor Subsystem (Total = 99mA)
   i) GPS(HiLetgo NEO6MV2)[10] → 6.7mA
   ii) Wind Vane Encoder[19] → 80mA
   iii) Speedometer IMU(Adafruit BNO055)[11]→12.3mA
c) Communication Subsystem (Total = 170mA)
   i) SiK V3 Telemetry Radio[12] → 100mA
   ii) FS-i6 Receiver→70 mA[17] (Found from forums since datasheet can't be found)
d) Power Subsystem (Total = 5.125 mA)
   i) 5V Charge Discharge Integrated Module [21] → 0.1mA
   ii) 3.3V Voltage Regulator [22] → 5mA
   iii) Battery Indicator Circuit [1] → 7.4V/300kOhm = 24.7 microAmps

Total Current Draw = 1.006 Amperes

Note: The 5V and 3.3V regulators are capable of outputting 2400mA and 800mA, respectively. Accounting for the components connected to each regulator, 5V components require 910mA (400mA + 160mA + 100mA + 70 mA + 80mA), and 3.3V components require 209.11mA (12.3mA + 0.11mA + 40mA + 6.7mA + 150mA). At their maximum capacities, they would not be drawing any more power than the regulators are capable of providing.

2.4.2.2 Battery Life

For the Li-Ion battery with 5.2Ah [20] capacity, we can only use 3.9Ah [16] of its capacity to ensure optimal voltage output. This will give us a total of **3.87 Hours** of operation.

2.4.2.3 Charging Speed

The battery can be charged at 1A from the included charging board. If charged from completely empty, it will take 5.2 hours to charge to full capacity. If charging within the reduced range of 3.9Ah (12.5% to 87.5%), it will take 3.9 hours.

3. Costs

3.1 Labor Cost:

The average starting salary of a graduate from the University of Illinois Urbana Champaign in the ECE program is $87,276 [2]. Since this salary is for a 52 week year, at 40 hours a week, this salary would come out to approximately $41.95 an hour.

Under the assumption that 3 weekly hours of work should be dedicated to each credit hour a class is worth, each team member should be working 12 hours a week on the project. So, for 3 team members, that would come out to 36 hours per week worked. The TA also has weekly meetings with us, so for the hour meeting, and an estimated extra hour for checking emails periodically, we would be at 38. Professor Fliflet also dedicates some time of his week to our project, so our safest estimate would be 40 hours per week that would need to be compensated.

Each semester is 16 weeks, but we started work on the project on the 4th week, so there will be 12 weeks total that will be compensated. In total, $20,140.61 needs to be allocated towards the labor costs of this project.

3.2 Facility Cost:

The cost of using a machine shop at the Grainger College of Engineering is approximately $60 an hour [3]. Assuming we spend 5 hours a week using these design facilities, for half the time of the project, that would be about 30 hours of the space needed. This comes out to $1,800 for use of the space.

3.3 Materials Cost:

We already have many of these resources available to us, but most will need to be reordered. However, we will account for the unit costs, in today's value, of all the resources we will be needing in total.

Part	Manufacturer	Part Number	Qty	Unit Cost	Total Cost
Microcontroller	STMicroelecrronics	STM32F103C8T6	1	$6.11	$6.11
Sail Winch Servo	Joysway Hobby	880545	1	$31.97	$31.97
Rudder Servo	Joysway Hobby	881504	1	$13.95	$13.95
BJT Transistor	Micro Commercial Co	2N3904-AP	4	$0.44	$1.76
1 kΩ Resistor	YAGEO	RC1206FR-101KL	2	$0.10	$0.20
4.7 kΩ Resistor	YAGEO	RC1206FR-104K7L	5	$0.10	$0.50
10 kΩ Resistor	YAGEO	RC1206FR-0710KL	1	$0.10	$0.10
20 kΩ Resistor	YAGEO	RC1206FR-0720KL	2	$0.10	$0.20
100 kΩ Resistor	YAGEO	RC1206FR-07100KL	5	$0.10	$0.50
4.7 µF Capacitor	Samsung Electro Mechanics	CL10A475KQ8NNWC	1	$0.10	$0.10
10 µF Capacitor	Samsung Electro Mechanics	CL21B106KPQNFNE	2	$0.27	$0.54
100 nF Capacitor	KEMET	C0603C104K8PAC7867	5	$0.18	$0.90
2 Pin Male Header	Molex	0022284028	3	$0.28	$0.84
3 Pin Male header	Molex	0022284036	2	$0.39	$0.78
5V Converter	MakerFocus	B07PZT3ZW2	1	$8.99	$8.99
3V3 Regulator	Texas Instruments	LM1117DT- 3.3/NOPB-ND	1	$1.81	$1.81
GPS Module	Hiletgo	GY-NEO6MV2	1	$8.99	$8.99
Wind Vane Encoder	US Digital	MA3-P10-125-B	1	$63.00	$63.00
Micro USB Port	Molex	1050170001	1	$0.51	$0.51
ARM 10 Pin Connector	Amphenol CS	G821EU210AGM00Y	1	$0.78	$0.78
Telemetry Radio	Holybro	SiK V3 17012	1	$58.99	$58.99
RC Controller	FlySky	FS-i6 6CH	1	$46.98	$46.98
RC Receiver	FlySky	FS-iA6	1	$0.00	$0.00
7.4 V Li-Ion Battery	Dantona Industries Inc.	L74A52-4-10-2WX	1	$18.96	$18.96
Speedometer IMU	Adafruit	BNO055	1	$34.95	$34.95
Battery Charger	DFRobot	DFR0564	1	$5.00	$5.00
SPDT Switch	ECE Supply shop	240156511	1	$1.30	$1.30
PCB	PCBWAY	—	1	$25.00	$25.00

Total Material Cost: $334.51

3.4 Total Cost:

The labor cost to complete this project is $20,140.61, the cost of the facilities is $1,800, and the material cost is $334.51. In total, this project would need to be funded $22,275.12.

To be safe, and account for any additional costs that may be incurred over the course of the project, whether that be damaged / lost parts, overtime, or any other circumstance, we would advise funding of $25,000 for the project in total.

4. Scheduling

Week	Main Goals	Austin	Devansh	Michael
5 (2/11 - 2-17)	Working on getting the boat operational in its current state to understand how it works. Start on the design document	Same for the week	Same for the week	Same for the week
6 (2/18 -2/24)	Start redesigning the PCB and obtain new equipment (speedometer + charger + LED), and replace any components that cannot be reused with the new PCB.	Research parts and determine what needs to be reordered. Work on design document.	Analyze PCB and look where new additions can be added. Work on design document.	Test PCB and work on setting up boat. Work on design document.
7 (2/25 - 3/2)	Begin changing the code to support the new components (speedometer + charger + LED), mainly the autonomous algorithm.	Work on PCB.	Ordering parts, salvaging old parts.	Research code and begin to make changes where needed for compatibility.
8 (3/3 - 3/9)	First Round PCB orders. Begin to set it up with any necessary soldering. Continue working on code	Work on PCB	Continue receiving orders, begin organizing resources and working on code.	Work on code.
9 (3/10 - 3/16) [spring break]	FINISH PCB DESIGN FOR SECOND ROUND	PCB	Work on code	Work on code
10 (3/17 - 3/23)	Finish PCB, Revise Design Document, Receive Orders, Work on code	Finish PCB	Work on code	Work on code
11 (3/24 - 3/30)	Begin redesigning the ship with the new components and PCB.	Soldering if available	Work on code	Work on code
12 (3/31 - 4/6)	Testing and optimization	When available, 2 people should go out to test, and the other member will be working on code remotely for real time updates.	Same	Same
13 (4/7 - 4/13)	Testing and optimization	Same as last week	Same as last week	Same as last week
14 - onward (4/14)	Project has to be done by this point, in terms of operation. Prepare for the mock demo, and begin work on the final documents, presentations, etc.	Project reports, demos, presentations.	Project reports, demos, presentations.	Project reports, demos, presentations.

5. Ethics and Safety

5.1 Ethics:

This project is a follow-up project to the Autonomous Sailboat senior design project done in 2022, furthermore it is definitely not the first Autonomous Sailboat project published throughout the internet, this brings the concern of originality and accreditation. An ethics policy that will be heavily taken into consideration is Section 7.6 of the IEEE Code of Ethics I.5 states, “to seek, accept, and offer honest criticism of technical work… and to properly credit the contributions of others” [4]. We will ensure to credit and cite any resources from previous projects and online and/or offline resources we use.

Furthermore, through our goal of making a seamless system of dual-mode control, we aim to adhere with the first IEEE Code of Ethics “to accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment;". By enabling a dual-mode capability, the project aligns with this ethical guideline by ensuring that users can take control in situations that may require human judgment or intervention, thereby protecting the public and the environment from potential harm.

Finally, one of the mission and goal of this project, which is to create a user-friendly and more affordable autonomous sailboat, strongly addresses the fifth IEEE code of ethics, "to improve the understanding of technology; its appropriate application, and potential consequences;"

5.2 Boat and Team Safety and Data Privacy:

Since the boat is a water-based mode of transport, our team must ensure the safety of the electrical systems by encasing it within a waterproof section of the boat- so as not to ruin the machinery and circuitry and not pose any shocks of electrocution to our team and others using the boat. We will also ensure that the wiring connecting the servos to our casing will be protected against water damage, vibration and rolling.

We will follow the Lab Safety guidelines while working on the boat in the Senior Design Lab rooms while testing our circuits, sensors and soldering. As per OSHA guidelines for welding, cutting and soldering, we will ensure to work around a fire extinguisher or places with a fire-plan, wear protective clothing and gear such as goggles and gloves [5].

Our ground control system will allow users to monitor sensor data such as GPS coordinates. The ethical concerns about that would be that the user's GPS coordinates would also be recorded as the "home base", which would pose a risk to the controller's privacy. In order to ensure that there are no privacy violations, we will protect and not monitor user data and uphold the IEE code I.1; "to hold paramount, the safety, health, and welfare of the public... and to protect the privacy of others".

5.3 Boat Operation and Demo Safety:

When testing in the lab, we are able to stay safe by operating the boat in a static environment, where no retrieval is necessary. We will maintain safety standards by working in a clean, uncluttered area, using a stable surface (the boat on its stand resting on a desk or floor). When using external tools, such as a box fan (for simulating wind), we will clear the area of any hazards that could be dislodged and damaged by the movement of air.

However, the boat must be operated in a free body of water, which may not be publicly accessible for swimming, or safe to do so. If the body of water being used for demonstration is being actively used by other groups, any testing should be postponed until the pond is completely clear. Fishing, boats, or any other use of the water may introduce unnecessary hazards that could negatively impact the performance or damage the boat.

If the boat is to become inoperable, due to loss of power or dislodged connections, we must wait for the wind to blow the boat to a safe location at the end of the pond. Simply using a string attached to the boat is not a safe option, as it can introduce unwanted resistance to the motion of the boat, get caught on something, or not be long enough. A string would not guarantee retrieval either, as if it gets caught, the boat could be impossible to retrieve without entering the water. As a team, we will ensure that we will remain vigilant while testing the boat in open waters and not hesitate to call “return to base” whenever required- removing the boat from a potentially hazardous situation and returning it to us.

If the weather is particularly poor, we will postpone the testing or demonstration to a more favorable day. Ideal weather would be defined as light to moderate wind, no precipitation, and above freezing (50°F or higher preferred). Any other conditions would risk damaging the boat, our components, or ourselves. High winds, especially above 25 mph not only lead to possible damage to the sails, but will generate large waves in water bodies and risk damaging or even capsizing the boat [24]. Precipitation would lead to a major increase in the risk of our components getting water damaged and gettied fried- leading to not just critical damage to the boat’s infrastructure, but also to us as we handle the boat. In the case of water damage such as that, we will ensure that once the boat is on land, we will only handle it by the insulated wooden exterior and leave it out to dry for at least 24h.

Our ideal testing location would be at the Arboretum, since it is the most easily accessible body of water from campus. Transportation of the boat over a walk that would take more than 10 minutes should only be done with car or bus, as to prevent fatigue, which could lead to the boat getting dropped. The risk associated with the Arboretum is that it is a popular destination on Campus during springtime, and there might be some disturbances in the water from local wildlife such as geese. To combat these issues, we can stay on the lookout for animals and other birds which could deal damage to the boat, and try to test in an area which is not too densely occupied by people. If we are unable to find a satisfactory location, we will cancel the test on that day and try again at another time. As a group, we ensure to never test the boat on open water during nighttime. The main concern would be the lack of visibility making it significantly tougher for us to be on the lookout for potential hazards. Furthermore, it would be hard to visually keep track of the boat- leading to higher chances of it getting lost, damaged or stolen if we are not able to realize that we need to invoke “return to base”.

References

[1] "Arduino Battery Voltage Indicator." Autodesk Instructables, https://www.instructables.com/Arduino-Battery-Voltage-Indicator/.
[2] “Electrical Engineering.” *Electrical Engineering*, The Grainger College of Engineering, grainger.illinois.edu/academics/undergraduate/majors-and-minors/electrical-engineering
[3] “Machine Shop” The Grainger College of Engineering, https://physics.illinois.edu/research/facilities/machine-shop
[4] “IEEE code of ethics,” IEEE, Jun-2020. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: 8-Feb-2024].
[5] ‘OSHA 1910.252- General requirements,” OSHA, March 26th, 2012. [Online]. Available: https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.252 [Accessed: 21-Feb-2024]
[6] Baker, Riley, et al. 2022, Autonomous Sailboat.
[7] "The Physics of Sailing: What You Should Know." MySail Team News, MySail, https://news.mysail.team/learn-to-sail/the-physics-of-sailing-what-you-should-know/. Accessed 21 Feb. 2024.
[8] "Tacking and Gybing." Wellesley College, Wellesley College, http://web.wellesley.edu/Athletics/PE-old/sailing/sailing_tacking.html. Accessed 21 Feb. 2024.
[9] "LSM303DLHC Data Sheet." Adafruit, https://cdn-shop.adafruit.com/datasheets/LSM303DLHC.PDF. Accessed 4 Mar. 2024.
[10] "NEO-6 Series Data Sheet." U-blox, https://content.u-blox.com/sites/default/files/products/documents/NEO-6_DataSheet_%28GPS.G6-HW-09005%29.pdf. Accessed 4 Mar. 2024.
[11] "BNO055 Intelligent 9-axis Absolute Orientation Sensor." Adafruit, https://cdn-shop.adafruit.com/datasheets/BST_BNO055_DS000_12.pdf. Accessed 4 Mar. 2024.
[12] "Sik Telemetry Radio V3." HolyBro, https://holybro.com/products/sik-telemetry-radio-v3?variant=41562952270013. Accessed 4 Mar. 2024.

[13] "STM32F103C8 Datasheet." STMicroelectronics, https://www.st.com/resource/en/datasheet/stm32f103c8.pdf. Accessed 4 Mar. 2024.
[14] "Sail Winch Servo Set DF65." Radio Sailing, https://radiosailing.net/products/sail-winch-servo-set-df65. Accessed 4 Mar. 2024.
[15] "New Digital Metal Gear Rudder Servo." Radio Sailing, https://radiosailing.net/products/new-digital-metal-gear-rudder-servo. Accessed 4 Mar. 2024.
[16] "Lithium Polymer Discharge Characteristics." Battery University, https://batteryuniversity.com/article/arquus_lithium-polymer. Accessed 4 Mar. 2024.
[17] "Flysky FS-i6 Receiver Current Draw." RCGroups Forum, https://www.rcgroups.com/forums/showthread.php?2963479-Flysky-FS-i6-Receiver-Current-Draw. Accessed 4 Mar. 2024.
[18] "5mm LED Datasheet." Components101, https://components101.com/sites/default/files/component_datasheet/5mm-LED-Datasheet.pdf. Accessed 4 Mar. 2024.
[19] "LED 5MM RED DOMED CLR 631NM." RS Components, https://docs.rs-online.com/32f2/0900766b81059a65.pdf. Accessed 4 Mar. 2024.
[20] "L37A52-2-1-3WA3/13692679" Digi-Key Electronics, https://www.digikey.com/en/products/detail/dantona-industries/L37A52-2-1-3WA3/13692679. Accessed 4 Mar. 2024.
[21] “5V Charge Discharge Integrated Module” Amazon, https://www.amazon.com/MakerFocus-Discharge-Integrated-Charging-Protection/dp/B07PZT3ZW2
[22] “LM1117DT-3.3/NOPB” Digi-Key Electronics, https://www.digikey.com/en/products/detail/texas-instruments/LM1117DT-3-3-NOPB/363583
[23] “Reading Battery Voltage with the STM32’s ADC” Vivonomicon, https://vivonomicon.com/2019/10/15/reading-battery-voltage-with-the-stm32s-adc/
[24] “Beaufort Wind Scale”, Weather.gov, https://www.weather.gov/mfl/beaufort