Autonomous Sailboat

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.

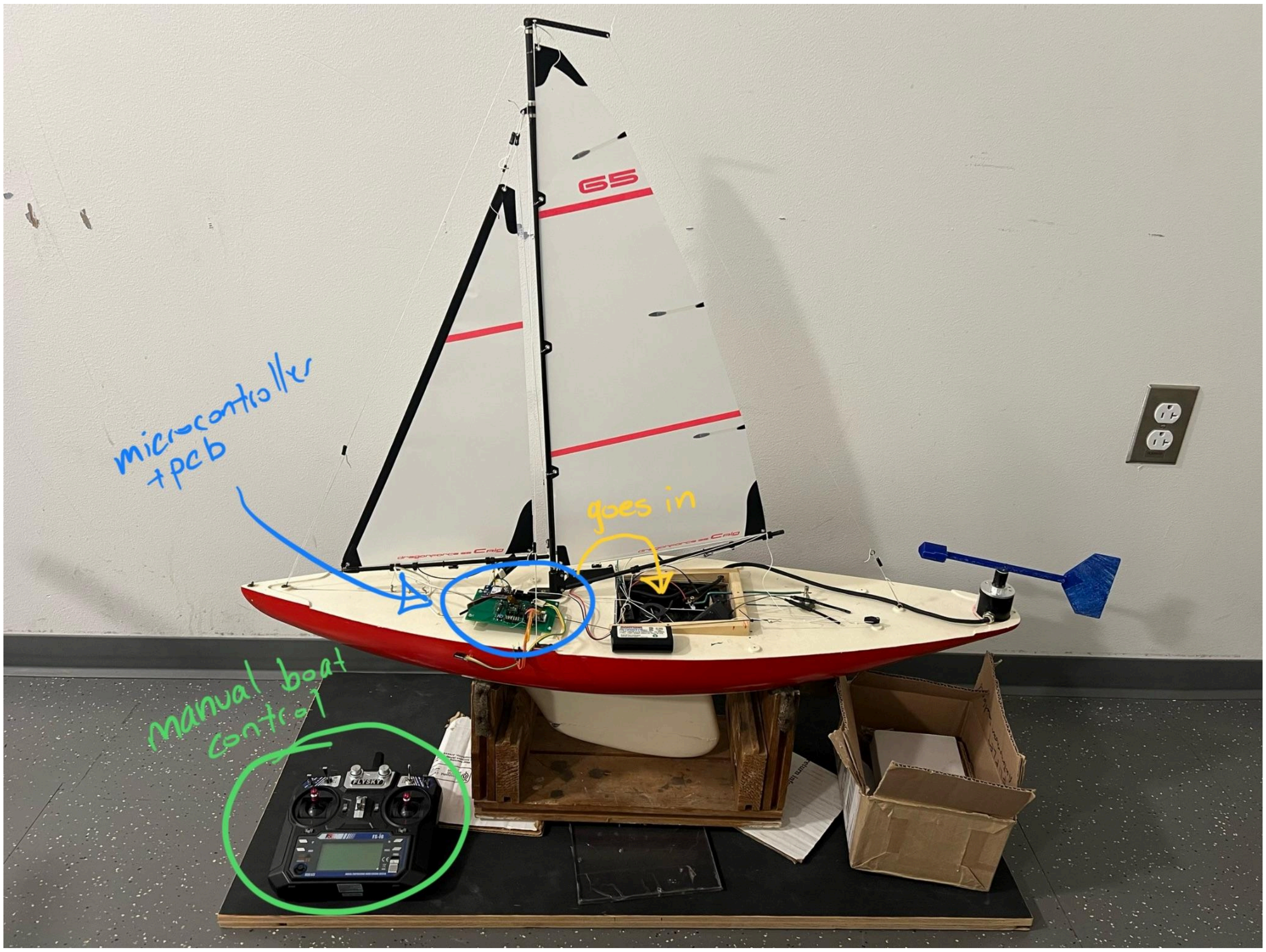
Given these factors, a boat should be able to direct itself towards a destination along a desired path.

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:

With our project, our main priority is improving (and proving) the autonomous capabilities of the boat. To have a successful project, we expect to be able to:

1. Calculate the ideal mast and rudder position given a desired direction, compass reading, GPS location, boat speed and wind direction, updating every 10s.
2. Follow a path defined by GPS coordinates on an open body of water with accuracy of ±3m.
3. With the ideal wind conditions, the boat will travel in a straight line with corrections within ±4°
4. Using the remote control, autonomous navigation can be enabled or disabled, allowing for manual control of the boat.
5. Abandon course and direct to a predefined “base” location autonomously when called by the remote control.

6. Send travel data wirelessly to a receiving computer, which can read the real time location of the boat along its path, as well as read out other sensor data generated on the boat, using telemetric systems.

2. Design:

2.1 Block Diagram:

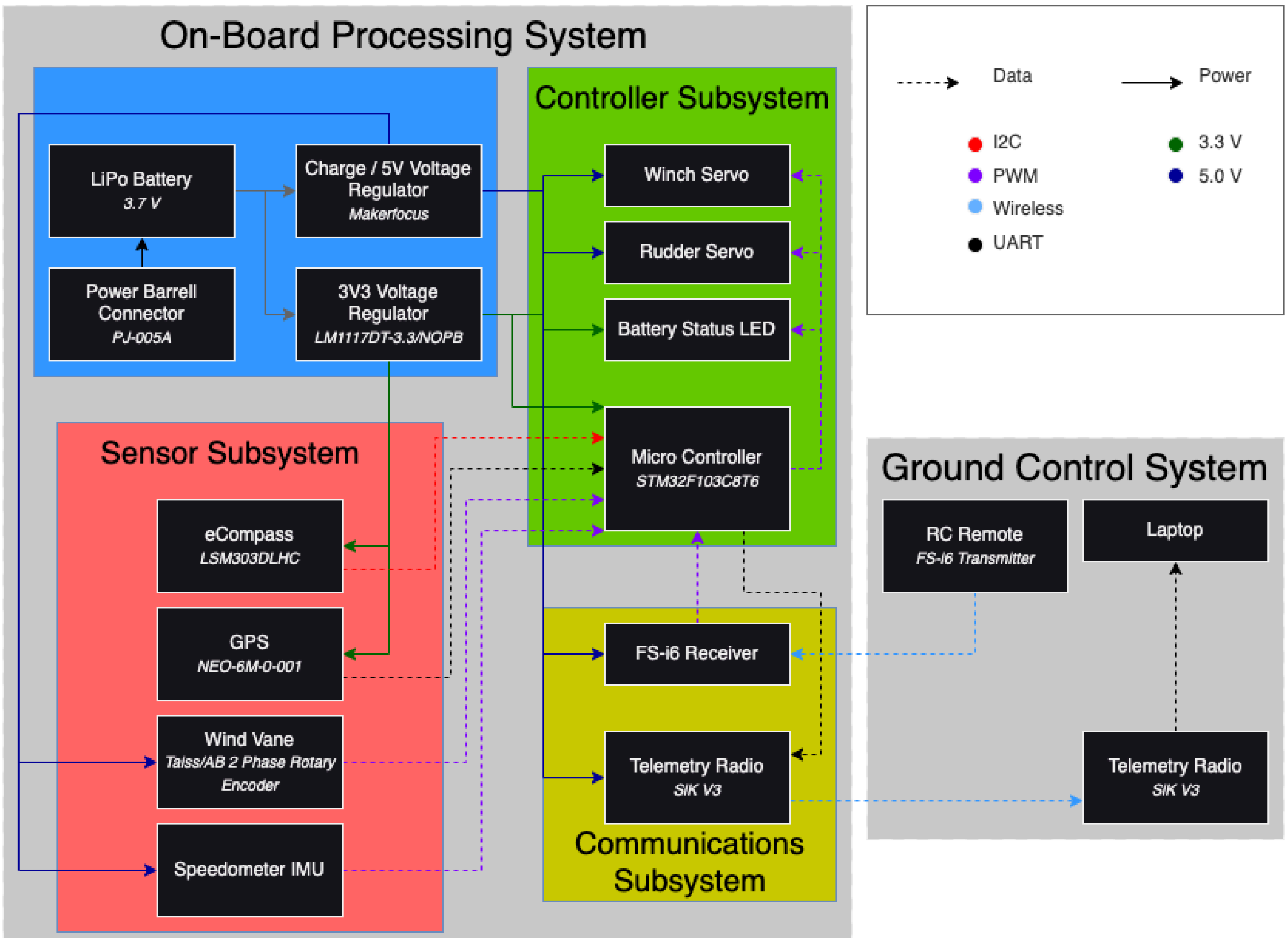


Figure 1: Block Diagram

2.2 Subsystem Overview:

2.2.1 Controller Subsystem:

The control subsystem is central to both operation of the sailboat in autonomous mode and manual mode. It is the heart of the sailboat's functionality and is what allows the sailboat to move and function. It fundamentally interfaces with the Power Subsystem to provide power for the microcontroller and the rudder and winch servos.

The autonomous features that will be developed and its requirements include:

1. Ability to trim sails according to the measured Apparent Wind Angle(AWA)
2. Ability to adjust sail chord angle to optimize speed based on current speed

3. Ability to hold a given compass heading to destination
4. Ability to sail to a destination

To do so, certain requirements have to be met by the different subsystems including the control subsystem which is responsible for the controller algorithm

a) Microcontroller:

In autonomous mode, the microcontroller takes data from the Sensor Subsystem (eCompass, GPS, WindVane, Speed Sensor) and uses that data to calculate the appropriate angles for the winch and rudder servos. The correct movement of these servos is essential to keeping the sailboat in its course and in upright position

In manual mode, the microcontroller interfaces with the Ground Control System through wireless receivers and the Telemetry Radio. It will adjust the angles of the servo and rudder servos based on the input received from the transceiver.

Requirement 1: We should be able to adjust servo angles with a tolerance of ±2°.

Requirement 2: Should not be able to call "Return to base" function if the boat is <5m away from the base

Requirement 3: Should be able to be set a destination and calculate the destination compass heading

Requirement 4: Should be able to maneuver the boat through moving the rudder angle and the sail chord angle to keep it in an average deviation of ±4° between course sailed and the destination compass heading.

b) Winch Servo

The winch servo serves the purpose of rotating the sails of the boat according to the instructions of the microcontroller, which would allow us to adjust the sail chord angle (SCA), that is, the angle the sail chord makes with the hull centerline. This value needs to be adjusted to a preset optimum value based on the apparent wind angle. Too large of an SCA will cause luffing and too small of an SCA will cause stalling which both greatly reduces sail lift force. It is powered with 5V by the Charge/Voltage Regulator from the Power Subsystem.

Requirement 1: Should be able to respond to PWM from microcontroller and move to specified angle with maximum error of 2°. It is a hobby RC servo and this is definitely in its capabilities

Requirement 2: Sail chord angle has to be set by the microcontroller to not cause a stalling when wind is strong as it can capsize the sailboat. This can be achieved by increasing the sail chord angle.

c) Rudder Servo

The rudder servo is used to rotate the rudder of the boat according to the instructions of the microcontroller, which would allow us to steer the boat. The rudder angle helps the boat compensate for getting blown off course from the destination due to pressure in the sails. This component is integral in keeping a compass heading to the destination. It is powered with a 5V supply by the Charge/Voltage Regulator from Power Subsystem.

Requirement 1: Should be able to respond to PWM from microcontroller and move to specified angle with maximum error of 2°. It is a hobby RC servo and this is definitely in its capabilities

d) LED

The LED will be mounted on the top of the sail, or any other visible location, and will indicate the remaining battery life of the boat.

Requirement 1: Should be able to visibly indicate at least 3 different battery levels through the brightness or dimness of the LED.

2.2.2 Power Subsystem:

Requirements:
Requirement 1: Must be able regulate battery voltage to power components throughout the discharge cycle of the battery to +- 0.1 V fluctuations
Requirement 2: Must be able to automatically cut out power when battery voltage drops too low
Requirement 3: The battery must be able to be recharged via the Power Barrel connector within 4 hours.
Requirement 4:The battery should be able to last minimum of 3 hours from a full charge when boat is used for testing
Requirement 5: The power subsystem should not short circuit under the conditions of water splashing and during boat use

a) Battery (3.7 V LiPo):

The battery will be wired to a 3.3V and 5V Voltage regulator, which will in turn power all of the Control, Sensor, and Communication Subsystem.

b) 5V Voltage Regulator (Makerfocus)

The 5V Regulator will supply constant power for the Winch Servo and Rudder Servo from the Controller Subsystem, the Wind Vane Encoder and Speedometer from the Sensor Subsystem, and the Telemetry Radio and Receivers for the Communication Subsystem.

c) 3.3V Voltage Regulator (LM1117DT-3.3/NOPB)

The 3.3V Regulator will supply constant power for the Microcontroller from the Controller Subsystem and the eCompass and GPS from the Sensor Subsystem.

d) Power Barrel Connector (PJ-005A)

The Power Barrel Connector would be used to set up the battery charging port to allow for ease of use for charging.

2.2.3 Sensor Subsystem:

a) eCompass and Accelerometer (LSM303DLHC)

The eCompass will send the direction of the boat's travel to the microcontroller in order for the system to control itself and correct its path if it deviates from the desired direction. The LSM202DLHC also has a built-in accelerometer which we will use to calculate the speed of the boat.

Requirement 1: The eCompass should be able to monitor the direction of travel with a tolerance of ±10°.
Requirement 2: The accelerometer should be able to detect acceleration with a tolerance of ±1 m/s^2

b) GPS (NEO-6G)

The GPS 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.

Requirement 1: The GPS should be able to determine coordinates of boat to an accuracy ±2.5m

c) Wind Vane (MA3 Miniature Absolute Magnetic Shaft Encoder)

The wind vane will inform the microcontroller of the Apparent wind angle which is important for adjusting sail .

Requirement 1: The MA3 should be able 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.

d) Speedometer IMU

Being able to measure boat speed is a valuable tool for optimizing sail trim, as we can point closer to the breeze as our speed increases. And generally increasing the self-awareness of the autonomous boat.

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

Requirement 1: The IMU should be able to estimate speed to accuracy of approximately >=0.1m/s

2.2.4 Communication Subsystem:

The communication subsystem is to transfer data to and from the Ground Control Subsystem.

a) Telemetry Radio (SiK V3)

The Telemetry Radio is used to transfer data about the servo, sensor, position, and microcontroller calculations to the Ground Control Subsystem. It operates at 915MHz.

Requirement 1: The Radio should transfer data with minimal loss or error.
Requirement 2 : The data from the microcontroller has to be properly transmitted with latency of less than 60 ms through the telemetry radio

b) FS-I6 Receiver

This wireless receiver would be used when the boat is in manual mode. It receives the user control input which it will then delegate to the microcontroller to control the servos. It also receives the boat autonomous mode ON/OFF signals and “return to base” signal to do these appropriate actions. It operates at 2.4GHz, and has 6 channels.

Requirement 1: The receiver should not respond to signals from the joystick channels of the transmitter when in autonomous mode

Requirement 2: 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.

2.2.5 Ground Control Subsystem:

The ground control subsystem is used to manually control the sailboat when in manual mode and to activate the “return to base” function when needed. It is also used to track the data on servo, sensor, position, and microcontroller calculations through the data it receives from the Telemetry Radio.

a) FS-16 Transmitter

The wireless transmitter sends user commands from the control panel to the onboard processing system when the boat is in manual mode. It also forwards signals to activate or deactivate autonomous mode and initiates the "return to base" command to the onboard system. It operates at 2.4GHz, and has 5 channels.

Requirement 1: The FS-I6 transmitter should transmit signals to the appropriate channel to move the appropriate servo in manual mode

b) Telemetry Radio Receiver

Receives data from the Telemetry Radio Transmitter in the communication subsystem. It operates at 915MHz, and communicates with a laptop via a UART connection.

2.2.6 Subsystem Interactions:

a) Sail Control Interactions:

Subsystems involved:
Controller: Microcontroller, Rudder Servo, Winch Servo
Sensor: Speedometer IMU, WindVane Encoder
Power: 5V Voltage Regulator

To sail in the right direction, we have to implement a control system that requires interaction between the Microcontroller from the controller subsystem and various sensors from the sensor subsystem.
The wind vane encoder from the sensor subsystem measures the apparent wind angle which becomes an input to the PID controller algorithm run by the microcontroller. The speedometer IMU also feeds its data to the microcontroller, where the data would be processed to become an estimation of the sailboat speed. This speed is used in the control algorithm to optimize sail trim.

Both these subsystems also fundamentally interact with the power subsystem because the sensors and microcontroller require 5V to run which is provided by the Voltage regulator.

b) Manual Control Interactions:

Subsystems involved:
Controller: Microcontroller, Rudder Servo, Winch Servo
Communication: FS-I6 Receiver
Ground Control: RC Remote(FS-I6 Transmitter)
Power: 5V Voltage Regulator

In the case that manual control mode is on, control is passed to the RC remote control that is part of the ground control subsystem. In this case, the interactions between the ground control subsystem, communication subsystem, and controller subsystem become paramount.

The RC remote control is a 6 channel FS-I6 Transmitter where each of its joystick axis and the buttons on the remote are channels. The controller subsystem needs the signals from these channels to move the sail winch and rudder servo accordingly. The in-boat 6-channel FS-I6 Receiver from the communication subsystem receives these signals from the remote controller and delegates it to the microcontroller of the controller system. The microcontroller will then send the appropriate pulse width modulation signals to the rudder and sail winch servo to adjust its angles.

The receiver also receives the “Back to base” signal from channel 5 of the remote, which when delegated to the microcontroller will execute the back to base function of the sailboat.

All these components involved are also fundamentally connected to the power subsystem because they need 5V to run which is provided by the 5V voltage regulator.

c) Navigation Control Interactions:

Subsystems involved:
Controller: Microcontroller, Rudder Servo, Winch Servo
Sensor: eCompass, GPS
Communication: Telemetry Radio SiK V3
Ground Control: Telemetry Radio SiK V3, Laptop
Power: 5V Voltage Regulator, 3.3V Voltage Regulator

To assign a destination and go in the appropriate heading of destination, there needs to be a way to control and track navigation.

The compass and GPS sensors are connected to the microcontroller where its data would be used as feedback for the PID control algorithm to adjust the winch and rudder servo angles for an optimal compass heading to the desired destination of the sailboat. The data from these sensors are also sent to the laptop in the ground control system via the telemetry radios on both the communication subsystem and the ground subsystem. This allows the sailboat operator to view the data which may come in useful.

The components from the controller and communication subsystems all interact with the 5V regulator from the power subsystem which supplies the components with 5v voltage. Whereas the GPS and eCompass are supplied with a 3.3V Voltage from the 3.3 voltage regulator.

d) Battery Status and Charging Interaction

Subsystems involved:
Controller: Battery Status LED
Power: 3.3V Voltage Regulator, LiPo Battery, Power Barrel Connector

For battery charging the LiPo Battery is connected to the Power Barrel Connector which allows for charging. The LiPo Battery is connected to the battery status LED through circuit shown in Figure 1.1 [3]. This circuit keeps the LED_ref to have a constant current of 1mA, whereas the LED_var will operate on frequencies 1 mA to 10mA depending on the percentage of the battery voltage. The zener diode Dz makes the current change as the voltage changes.

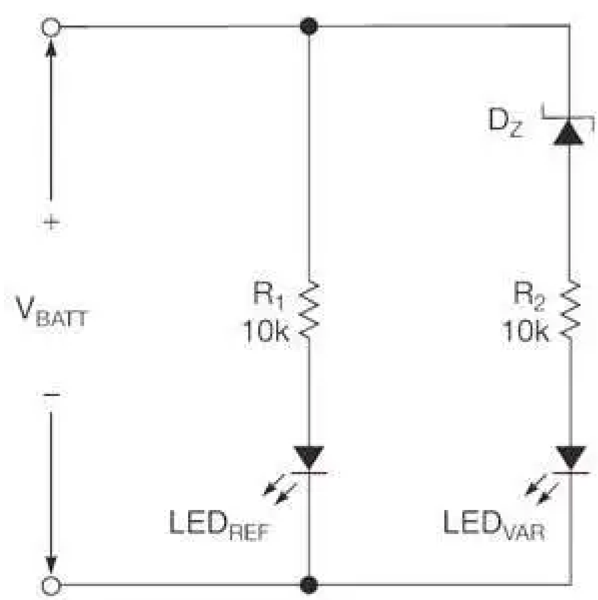


Figure 2: LED Indicator Circuit

2.4 Tolerance Analysis:

2.4.1- Angles and Center of Mass

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

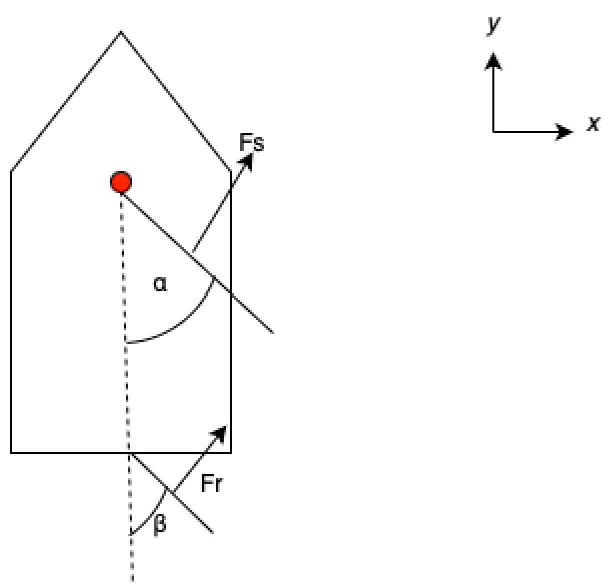


Figure 3: Free Body Diagram of Sailboat

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.

3. Ethics and Safety

3.1 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” [1]. 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;"[1]. 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;"

3.2 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.

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” [1].

3.3 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 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.

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 degrees or higher fahrenheit preferred). Any other conditions would risk damaging the boat, our components, or ourselves.

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.

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.

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.

References

[1] “IEEE code of ethics,” IEEE, Jun-2020. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: 8-Feb-2024].
[2] Baker, Riley, et al. 2022, *Autonomous Sailboat*.
[3] "Simple Battery Status Indicator Uses Two LEDs." EDN, www.edn.com/simple-battery-status-indicator-uses-two-leds/. [Accessed: 21-Feb-2024].

https://news.mysail.team/learn-to-sail/the-physics-of-sailing-what-you-should-know/

http://web.wellesley.edu/Athletics/PE-old/sailing/sailing_tacking.html\