Autonomous Sailboat

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Project-43

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Abstract

There is a large barrier to entry in learning how to operate a sailboat. Using a sailboat is very complex and people often have to spend many weeks or even months just learning the basics. This prevents many people from enjoying this activity simply because they may not have the time to learn. On the other hand the capabilities of autonomous machines have advanced rapidly in recent years. It is now possible to have machines do things that would have required a person many hours of training just a few years before. Thus we propose the idea of an autonomous sailboat that would be capable of sailing without any input from a user.

Contents

1. Introduction

1.1 Objective

An autonomous sailboat would have many advantages over a normal sailboat. One of the major benefits to operating an autonomous sailboat is that it would not require significant training unlike a normal sailboat. Sailing a boat by hand is frequently very difficult. In order for a user to sail the boat to a desired destination, they must be able to determine the location of the boat relative to the destination, judge the direction of the wind then calculate the optimal position of the sails/rudder in order to move the boat in the direction of the destination. A user also needs to perform many complex maneuvers such as tacking,whereby the user moves back and forth at 45 degree angles into the wind in order to move upwind, and jibing, whereby the sailboat heading turns its stern through the wind in order to sail downwind. Thus a long training process is necessary for anyone who would like to use a sailboat. An autonomous sailboat would allow people to use sailboats without having to either go through a lengthy training process. Due to all of the complex maneuvers a person has to do, using a sailboat can also be a very dangerous activity with a high possibility of accidents due to the user mishandling the sailboat. With an autonomous sailboat there is a greatly reduced possibility of accidents that are caused by user error as the sailboat will not rely on a human in order to operate.

1.2 Background

The idea of an autonomous sailboat that would be able to navigate to and from a location without the need of a pilot has been proposed in the past but presents many significant obstacles [1], [2]. The sailboat must be able to ascertain which direction the boat is facing, The sailboat would also need to determine the direction of the wind while also manipulating the sails and the rudder so that it can steer itself in any direction.

In order for the boat to accomplish these missions while still being marketable the components used will need to be inexpensive so as not to increase the cost of the autonomous sailboat relative to other sailboats on the market. The various sensors used to gather information on the boat's environment must not be too bulky so as to avoid taking up space on the boat.

1.3. High Level Requirements

In order to achieve our goal of an autonomous sailboat it needed to meet several requirements:

- The boat control system must be able to record rudder and sail servo settings as well as sensor and heading data during both modes of operation at one second intervals for up to an hour of operation
- The boat must have two modes of operation: autonomous and user remote controlled, and the user must be able to switch between these modes while the boat is sailing.

- The boat autonomous control system must be able to autonomously sail the boat on a steady course on a heading ranging from 60 to 160 degrees relative to the wind direction by controlling the rudder and sail settings after the user has prepared the boat to sail in that direction

Due to time constraints and limitations we were forced to scale back our project's goals. Originally we intended to integrate a GPS into our design which would allow our autonomous sailboat to plot a course to the destination using GPS coordinates. One of the biggest dangers to a user is becoming lost when operating a sailboat as there are frequently very few landmarks when out at sea which can be very dangerous for the user if they do not know how to navigate back to shore. With this ability to plot a course using a GPS there would be no danger of a sailboat getting lost while navigating to its destination as the boat would be able to determine its own location relative to its objective. We also intended to implement a gyroscope which would help to improve accuracy in our sailing by accounting for the heel of the boat, how much from the vertical the boat leans as a result of the wind. We mounted the anemometer on top of the main mast of the sailboat and the tilt of the boat can negatively affect the accuracy of our calculations for the direction for the wind. Lastly we hope to make the system relatively simple to install even on boats that were initially designed to be non-autonomous allowing non-autonomous boats to be able to be converted into autonomous boats very easily. We also want to add some storage to our boat in order to record data which can be used for further improvements. The storage is not required for other boats but is recommended as we are able to obtain data from different types of boats.

2. Design

2.1 Block Diagram

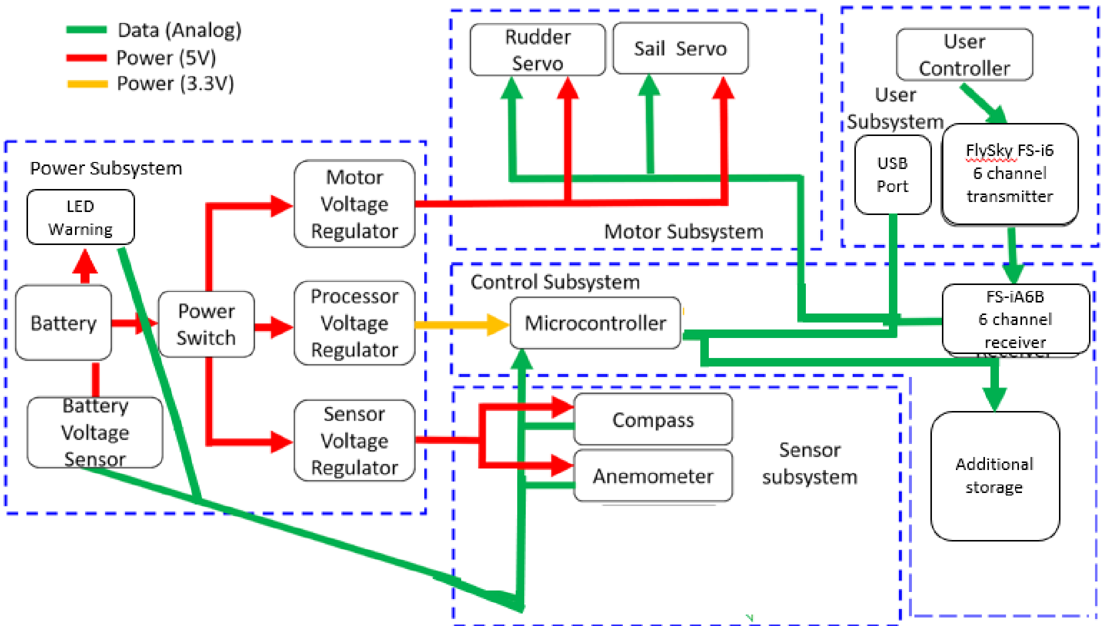

Figure 1: Block Diagram

Figure 1 shows how the autonomous boat will require five subsystems in order to function:

1. The power subsystem which will provide power to all of the components of the other subsystems. It will consist of a power supply and three voltage regulators, one for each the three other subsystems on the boat.
2. The sensor subsystem will use sensors in order to collect data from the boat's environment so that it will navigate on the water. It will consist of a compass and an anemometer.
3. The control subsystem will consist of a microcontroller that will process information from the sensor subsystem and determine what instructions to send to the motor subsystem in or to reach the desired destination. It will also use a receiver in order to process signals from the user input subsystem to switch between user and autonomous control and determine how to move the boat based on user input in user control mode.
4. The motor subsystem will get instructions from the microcontroller subsystem and use those instructions to determine how to control the sails and rudder of the boat in order to move the boat in the desired direction. It will consist of two servos used to control the two sails and rudder of the boat.
5. The user input subsystem will send a signal to the sailboat indicating that the user would like to switch from autonomous to user control mode or vice versa. In user control mode the subsystem will send commands from the user to the boat to sail the boat in a direction the user wants. It will consist of a controller that the user will input commands into and a transmitter that transmits those inputs to a receiver on the boat.

2.2 Boat Power Source Subsystem

The boat power source subsystem is required to power up all other subsystems by providing the other subsystems with appropriate voltage inputs. The battery voltage will need to be regulated to other voltages for the other subsystems to operate. The sailboat is powered by a battery pack of 4 AA batteries and is used to distribute power to all of the other subsystems.We considered using more powerful batteries that could last longer but we were concerned about overloading the circuit so we ultimately chose to use 4AA batteries. The batteries must supply +6V ± 2% with 10mA for at least 6 hours. The voltage regulator circuits are used to regulate the voltage and generate various voltage outputs to power subsystems which require voltages different from the battery voltage. The voltage must be regulated to 3.3V for the connection to the control subsystem and 5V for the connection to the other subsystems. Both must be regulated to a electrical current of 0.5mA ± 2%. In order to decide what values the resistors of the circuit must be we use the formula in Equation 1 where $V_{IN\ MAX}$ is 6V, $I_{Z\ MIN}$is the minimum current at which the Zener diode will operate (1mA),V_Z is the voltage we want outputted and $I_{OUT\ MAX}$is the maximum output current which is about 10mA. We can calculate the resistance of the connection to the control subsystem as R_1 = (6 – 3.3) / ((10 + 1) * 0.001) = 245.45 ohms and the resistance of the connection to the other subsystems as R_2= (6 – 5) / ((10 + 1) * 0.001) = 90.91 ohms

$$R_S = (V_{IN\ MAX} - V_Z)/(I_{OUT\ MAX} - I_{Z\ MIN}) \tag{1}$$

2.3 Boat Sensor Subsystem

The sensor subsystem is responsible for collecting all the data about the boat's heading using a LSM303DLHC compass. We also care about wind direction since we will be using a sail to propel the boat. An MA3 Magnetic Encoder will act as an anemometer and will provide the microcontroller with wind speed and direction for determining the direction of the sails. Both the compass and the anemometer must calculate the boat's heading relative to true north within 1-3 degrees with no more than 5 seconds latency.

$$Angle\ of\ Boat\ Heading\ =\ Time\ MA3\ PWM\ Signal\ is\ high\ /1023\ *\ 360 \tag{2}$$

2.4 Boat Control Subsystem

The control subsystem accepts data from the sensor subsystem, and calculates the angles the sails and rudders need to be at to sail to the destination. It then sends instructions to the steering subsystem. The sail boat will use an Arduino Uno board which holds the software that interprets sensor data and determines how the boat should navigate. We considered using a PCB board with an ATMega328P microcontroller instead of the Arduino Uno but we found that the Arduino Uno was significantly easier to use and install onto the boat. The Arduino should be able to receive data from the compass and anemometer in the sensor subsystem. It must be able to calculate boat heading and the direction of the wind with relative errors within 1-5% in magnitude with no more than 5 seconds latency. To accomplish this, the Arduino will read in the I2c data signal from the LSM303DLHC compass to get the direction and convert the PWM signal from the MA3 encoder into an angle using the formula in Equation 2. The Arduino also needs to send an analog signal containing instructions to the servos based on information from sensors. The processor subsystem will also include a FS-iA6B 6 channel receiver that must be able to interpolate user input commands from the controller and send them to the servos with latency no more than 0.1 seconds latency. Figure 2 shows how each of the sensors are connected to the Arduino Uno and how the power subsystem provides power to all of the components.

2.5 Circuit Schematics

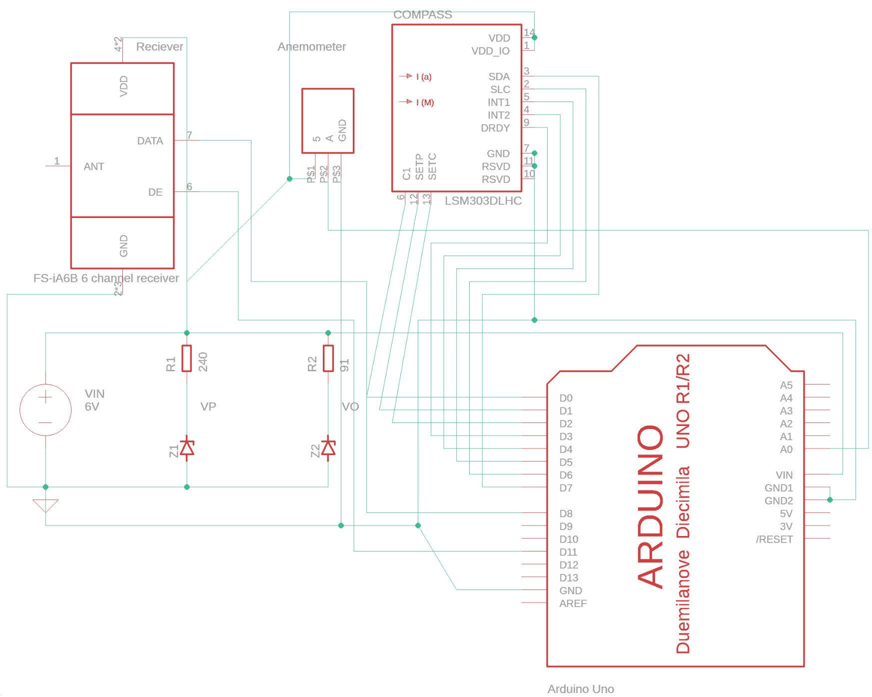

Figure 2: Circuit Schematic of our autonomous boat control

2.6 Boat Steering/Servo Subsystem

The Boat Steering Subsystem contains the servos for steering the boat. It receives instructions from the processor subsystem then uses those instructions to adjust the angle of the sails and the rudder in order to steer the boat in the intended direction of travel. Using servos enables us to be precise in our angles of the sail and rudder without a tachometer. For the sails, the servos are connected to a winch that moves the mast. The servos must be able to turn to angles needed to perform sailing maneuvers within 1-5 degrees.

2.7 User Control Subsystem

The user control subsystem is designed to take in inputs from the user and transmit them to the sailboat so that when the boat is in user control mode the user can steer the boat to a destination. At times the user may want to take back control themselves such as if they would like to change course to a new destination. The subsystem consists of a user control and a FlySky FS-i6 6 channel transmitter. The transmitter must be capable of sending instructions to the receiver located on the boat from a distance of 100 meters.

2.8 Flowchart for Sailing Software

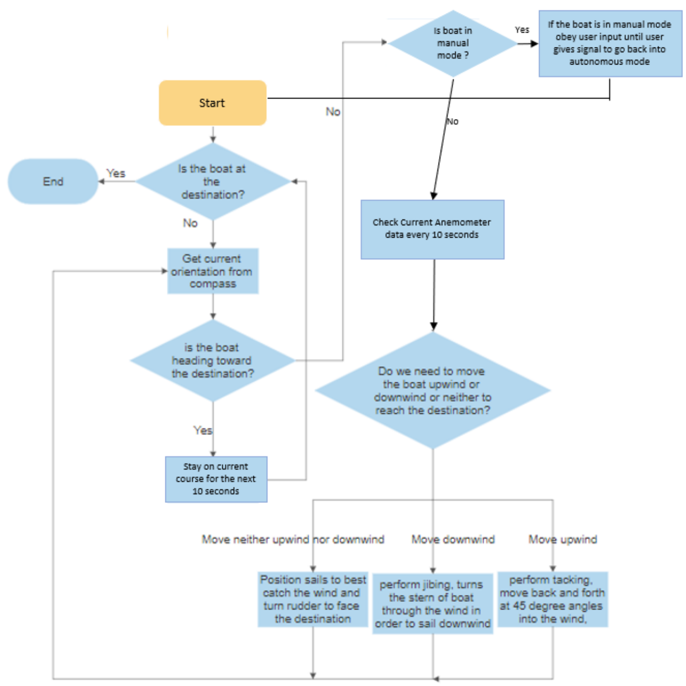

Figure 3: Flowchart of sailing software

Figure 3 describes the software program used by the microcontroller subsystem to control the boat. First the program determines whether the boat is at its destination or not. If it is at the destination the program ends. If it is not at the destination it gets the boat's current orientation from the compass and then checks whether the boat is heading towards the destination. If the boat is heading toward its destination the program instructs the boat to stay on its current course for the next 10 seconds then checks if the boat is at the destination again. If the boat is not on the correct course then the program checks whether the boat is in manual or autonomous mode. If it is in manual mode it obeys user inputs until the user switches back into autonomous mode after which the program checks to see if the boat is at the destination. If it is in autonomous mode, the program checks the anemometer data every 10 seconds to determine the direction of the wind. Once it has all of this data, the program will decide what maneuvers the boat will need to make in order to reach its destination (i.e. tacking, jibing or just shifting the rudder/sails). After having the boat complete these maneuvers the program will check the compass again and see it is heading in the correct direction to reach the boat’s destination.

3. Verifications

3.1 Boat Power Source Subsystem Verification

In order to verify that the power subsystem can provide power to all of the other subsystems we first test whether the 4AA batteries provide appropriate voltage. To do this we first use a multimeter to check whether the voltage of each one of 4 AA batteries is around 1.5V. After that we use a multimeter to check whether the whole battery pack can supply a voltage of 6V ± 2% with a current around 10mA. Then after the battery pack works for 6 hours, we measure the voltage again to check whether the whole battery pack can supply voltage 6V ± 2% with around 10mA. The results of our final measurements can be seen in the multimeter reading shown in Figure 4 which is within the margin of error for our expected outcome and match our requirements to power the whole circuit

We then test the voltage regulators by first using the multimeter to connect the positive and negative side of each of the voltage regulators. Then we check the display which should output around 3.3V for the connection to the control subsystem and 5V for the connection to the other subsystems. The final multimeter readings for the voltage regulators can be seen in Figure 5. The readings match our requirements and thus there is no chance of overloading the circuits.

Figure 4: Multimeter readings after 6 hours of running

Figure 5: Left-Multimeter Reading of 3.3V Power Supply, Right-Multimeter Reading of 5V Power Supply

3.2 Boat Sensor Subsystem Verification

In order to verify that the compass and anemometer can calculate the boat's heading and wind direction relative to true north respectively, we connect each device to the arduino and observe outputs. The outputs should be displayed within 5 seconds to meet the requirement of latency.
For the compass, we view the boat's heading information. We then point the compass in four directions (North, South, East and West) and compare with the actual directions to see whether they have errors within 2 degrees. Figure 6 shows the signal transmitted to the Arduino from the compass, demonstrating that the Arduino is receiving a signal from the compass.

For MA3 (anemometer), we view the wind direction information. We then change the direction of MA3 to simulate the change of wind direction. Then we compare the output with the actual direction of MA3 to see whether the error is within 1-3 degrees. Then we record the signal outputs using a multimeter. Figure 7 shows several multimeter readings and their corresponding angles.

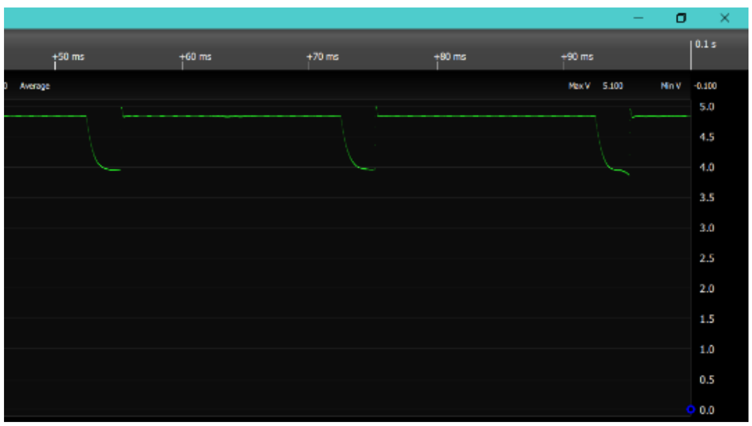

Figure 6: Graph of SCA Pin during the compass transferring heading data to Arduino controller

Figure 7: Multimeter Reading of anemometer
Left-around zero degrees (103.5mV), Middle-around 45 degrees (0.554 V), Right-around 270 degrees (3.912 V)

3.3 Boat Control Subsystem Verification

In order to verify that the boat control subsystem meets requirements we first test the Arduino to see if they receive signals from the compass and anemometer. We first use the compass to view the boat's heading. Then we change the boat's heading. If the output changes, the data the Arduino receives from the compass should change as well. We then use the anemometer to view the wind direction. We then move the fan to change wind direction. If the output changes, the data the Arduino receives from the anemometer should change as well. Our tests show that the Arduino successfully interpolate data from compass and annemeter. Figure 8 shows the changes as a result of moving the compass and anemometer.

Next we need to test whether the processor is able to calculate boat heading and wind direction with relative errors within 1-5% in magnitude with no more than 5 seconds latency. To test this we use the compass and anemometer to view the boat's heading and wind direction respectively. Then compare the recorded boat's direction and the wind direction outputted by compass and anemometer with the actual heading of the boat and wind direction and check if the relative error is within 1-5% in magnitude. The recorded information should be displayed within 5 seconds. Figure 8 shows the sailboat heading and wind direction calculated by the Arduino. When we compared the angles to the actual angles of the boat heading and wind direction they were within our margin of error.

Additionally, the Arduino must be able to send instructions to the servos. To test this we connect the servos to the microcontroller and record the correct information collected from the sensors and use them as input. We then observe how the sail/rudder servos move in response to signals from the sensors and record the signals sent from the Arduino to the servos using a multimeter. Figure 9 shows one of the PWM signals we recorded with different PWM signals corresponding to different angles and resulting in different servo movements

We also need to test the receiver on the boat to make sure it can receive user input commands from the controller and send them to the servos with latency no greater than 0.1 seconds. To test this we connect the receiver to the boat motor subsystem and input commands into the controller from 100 meters away. We then observe how the sail/rudder servos move in response to signals from the user input and record signals using a multimeter. We observed that the multimeter readings changed as a result of user input and the sail/rudder movement also match user input.

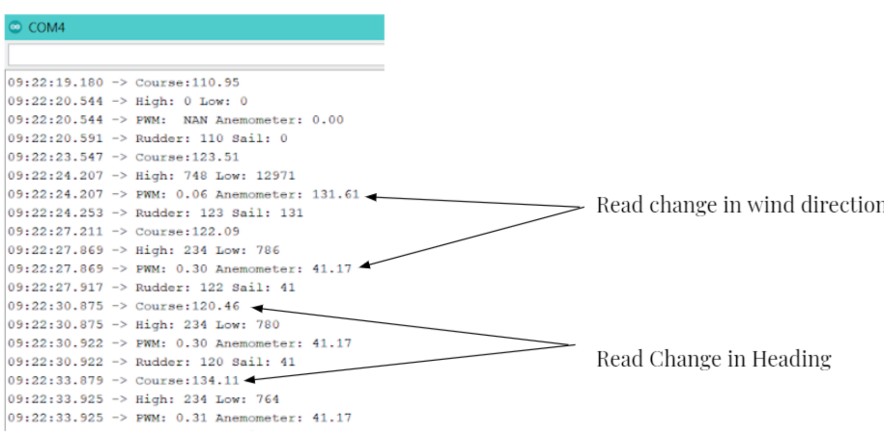

Figure 8: Outputs of Arduino show how the boat heading (Course) and wind heading (Anemometer) change as a result of changes in sensor

Figure 9: A graph and a multimeter reading of a PWM signal sent to the sail servo.
2.7% Duty Cycle

3.4 Boat Steering/Servo Subsystem Verification

In order to make sure that servos turn to angles needed, we measure the angles of the sail and rudder and compare them with input of the microcontroller to check whether the errors are within 5 degrees. Then we change the inputs and repeat the previous step. Figures 10 and 11 show how the servos moved as a result of our inputs.

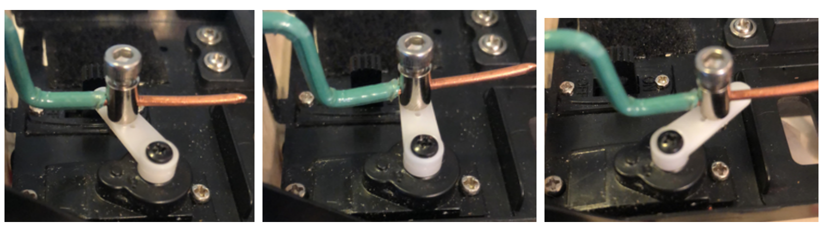
Figure 10: Angles of the rudder. Left-45 degrees, Middle-90 degrees, Right-135 degrees

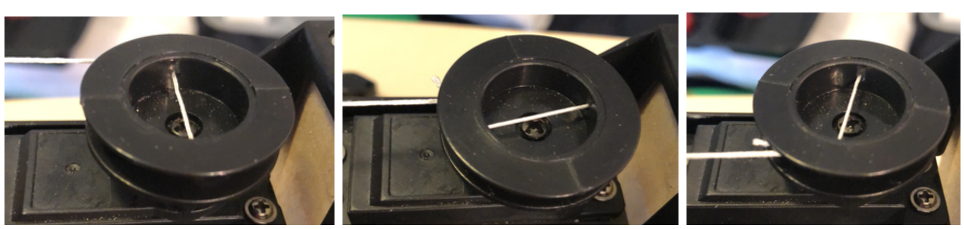
Figure 11: Angles of the sail. Left-90 degrees, Middle-135 degrees, Right-160 degrees

3.5 User Control Subsystem Verification

In order to test the requirement that the transmitter must be able to transmit user input commands to the boat from 100 meters away, we first switch the boat from autonomous control to user remote control. Then a person moves 100 meters away from the boat with the controller while others remain with the boat. Then the person inputs commands to the controller and checks whether the boat receives and executes the commands. It turns out that transmission of user commands to the boat succeeded from 100 meters away.

4. Cost and Schedule

4.1 Cost analysis

4.1.1 Labor Cost

Table 1. Labor Costs

Name	Hourly Rate	Hours	Total
Franklin Liu	$30	80	$2400
Haoyu Wang	$30	80	$2400
Megan Shapland	$30	80	$2400
Total			$7200

4.1.2 Part Cost

Table 2. Component Costs

Description	Quantity	Vendor	Cost / unit	Total Cost
ATmega328P	1	Digi-key	$2.51	$2.51
MA3 Absolute Encoder	1	AndyMark	$56	$56
PCBs	5	PCBWay	$1	$5
LSM303DLHC Module	1	Amazon	$6.19	$6.19
Total				$70.41

4.1.3 Grand Total

Table 3. Grand Total Cost (Labor + Part)

Section	Total
Labor	$7200
Parts	$70.41
Grand Total	$7270.41

5. Ethics & Safety

5.1 Boat Safety

One concern regarding the boat is the possibility of overloading the weight of the boat due to how many additional components we will have to add. An overloaded boat will have a large possibility of overturning, so as a safety measure we will carefully measure the weight of all components and make sure that the boat weight is less than the overload weight.
Furthermore, we want to avoid the components being damaged due to water exposure as this could cause a breakdown and leave the user stranded with no ability to steer the boat if something falls into the water unexpectedly. Thus every component we use should be waterproof to prevent these kinds of accidents.
Another concern is that there could be a great deal of damage to the boat if there is a collision.
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5.2 Electrical Hazards

There are several potential electrical hazards with our project. The battery could explode and damage other parts of the boat or even injure the user if the circuits are improperly wired. To avoid this we will make sure that we do not short batteries by adding some resistances in the circuit and carefully test our circuits before implementing them within the final system.
Additionally, batteries which are used up may pollute the environment if not disposed properly. We will prevent potential damage to the environment by making sure that every battery that is used up during experiments should be collected and disposed properly and providing any users with careful instructions on how to properly dispose of the batteries.

5.3 COVID-19 Contingency Planning

In order to avoid potential COVID-19 infections when testing and operating our autonomous boat design all group members will wear gloves and masks at all times. If the group is working indoors or outdoors we will maintain social distancing by being six feet apart from one another and make sure to ensure good ventilation. After completing all assignments we will clean and disinfect all surfaces and wash our hands thoroughly. We will also make sure that every member of the group is regularly tested for COVID-19 and if any member tests positive they will quarantine for two weeks [5].

6. Conclusion

Despite several setbacks such as not having enough time to install a GPS or a gyroscope on the boat, we were able to complete all three major requirements for our project. The Arduino Uno is capable of storing and printing out data from the sensor subsystem. The boat is capable of switching between autonomous control, where it relies on the Arduino and sensors, and user control, where it relies on user input and signals from the receiver. The autonomous control is capable of sailing the boat on a steady course on a heading ranging from 60 to 160 degrees relative to the wind direction by controlling the rudder and sail settings after the user has prepared the boat to sail in that direction. We used five different subsystems in order to accomplish this feat: the power subsystem, sensor subsystem, control subsystem, motor subsystem and user control subsystem.

6.1 Future Work

In the future we hope to continue work on this project and implement several other features. In order to switch between user and autonomous mode we used a relay that had to be flipped by hand. In the future we will want to have the ability to switch between user and autonomous control built into the transmitter. We were unable to test the boat out on water. We would like to do that in the future and take waterproof measures.The current data storage on the Arduino Uno is limited. We would like to add more data storage to the Arduino with a separate data storage system. We had a problem with servos over rotating and putting too much stress on the sails. We want to program in hard stops and better calibration to keep this from happening.

7. Appendix A: Requirement and Verification Tables

Table 4. Requirements and Verifications for Power Source Subsystem

Requirements	Verifications
4 AA Batteries - power source: 1) Supply +6V ± 2% with 10mA for at least 6 hours.	AA Batteries: 1.a. Use a multimeter to check whether the voltage of each one of 4 AA batteries is around 1.5V. 1.b. Use a multimeter to check whether the whole battery pack can supply voltage 6V ± 2% and the current should be around 10mA. 1.c. After the battery pack works for 6 hours, measure the voltage to check whether the whole battery pack can supply voltage 6V ± 2% with around 10mA.
Voltage Regulators: 1) Voltage must be regulated to 3.3V ± 2% and 0.5mA ± 2% as required for the microcontroller.	Voltage Regulator: 1.a. Use the multimeter to connect the positive and negative side of the voltage regulator. 1.b. The display should output around 3.3V. 1.c. Use the multimeter to check whether the current is 0.5mA ± 2%.

Table 5. Requirements and Verifications for Sensor Subsystem

Requirements	Verifications
LSM303DLHC -Compass: 1) Compass must calculate the boat's heading relative to true north within 1-3 degrees with no more than 5 seconds latency.	LSM303DLHC -Compass: 1.a. Connect the compass device to the microcontroller and computer to view the direction information. 1.b. Point the compass in four directions (North, South, East, West). 1.c. Compare the recorded directions outputted by the compass with the actual directions and check if it is within 2 degrees. The compass should also be able to display the direction within 5 seconds. 1.d. Record the signal outputs using a multimeter.

Table 5 continued

MA3-Anemometer: 1) Anemometer must calculate the wind's heading relative to true north within 1-3 degrees with no more than 5 seconds latency.	MA3-Anemometer: 1.a. Connect an anemometer device to the microcontroller and computer in order to view the direction information. 1.b. Use a fan to blow wind at the anemometer from four directions (North, South, East, West). 1.c. Compare the wind directions outputted by the anemometer with the direction the fan is pointed at and check if it is within 1-3 degrees. The anemometer should also be able to display the wind direction within 5 seconds. 1.d. Record the signal outputs using a multimeter.

Table 6. Requirements and Verifications for Control Subsystem

Requirements	**Verifications**
Arduino Uno - Microcontroller: 1) Microcontroller should be able to receive data from the compass and anemometer. 2) Processor must be able to tell which way to move the boat and what instructions to give the servos based on information from sensors.	Arduino Uno - Microcontroller: 1.a. Use a compass to view the boat's heading. 1.b. Change the boat's heading. If the output changes, the microcontroller receives data from the compass. 1.c.Use a fan to produce wind. 1.d. Use an anemometer to view the wind direction. 1.e. Move the fan to change wind direction. If the output changes, the microcontroller receives data from the anemometer.
2) Processor must be able to calculate boat heading and wind direction with relative errors within 1-5% in magnitude with no more than 5 seconds latency.	2.a. Use a compass to view the boat's heading. 2.b. Use an anemometer to view the wind direction. 2.c. Compare the recorded boat's direction and the wind direction outputted by compass and anemometer with the actual heading of the boat and wind direction and check if the relative error is within 1-5% in magnitude. The recorded information should be displayed within 5 seconds.

Table 6 continued

3) Processor must be able to tell which way to move the boat and what instructions to give the servos based on information from sensors.	3.a. Connect the servos to the microcontroller. 3.b. Record the correct information collected from the sensors and use them as input. 3.c. Observe how the sail/rudder servos move in response to signals from the sensors. 3.d. Record signals to servos using multimeter.
FS-iA6B 6 channel receiver: 1) Must be able to receive user input commands from the controller and send them to the servos with latency no more than 0.1 seconds latency	FS-iA6B 6 channel receiver: 1.a. Connect receiver to boat motor subsystem. 1.b. input commands into the controller from 100 meters away. 1.c. Observe how the sail/rudder servos move in response to signals from the user input. 1.d. Record signals using a multimeter.

Table 7. Requirements and Verifications for Steering/Servo Subsystem

Requirements	**Verifications**
Sail/Rudder Servos: 1) Servos must be able to turn to angles needed to perform sailing maneuvers within 1-5 degrees.	Sail/Rudder Servos: 1.a. Measure the angle of the sails relative to the angle inputted into the controller and see if it is within 1-5 degrees. 1.b. Repeat steps 2.a from four directions (North, South, East, West).

Table 8. Requirements and Verifications for User Input Subsystem

Requirements	**Verifications**
FlySky FS-i6 6 channel transmitter: 1) Must be able to transmit user input commands to the boat from 100 meters away.	FlySky FS-i6 6 channel transmitter: 1.a. Switch boat from autonomous to user control. 1.b. Move 100 meters away from the boat. 1.c. Input commands into the controller. 1.d. Observe how the boat responds to the inputs and see if they match up with the user commands.

8. Appendix B: References

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