ECE 4336 - Team 12

S.S. Autonomous Water Quality Monitor

Final Report

Customer: Todd Running, Houston-Galveston Area Council

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Date: 4/30/24

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Testimonial

The product specification for this device was approved by Todd Running and the Houston-Galveston Area Council team on March 4th, 2024.

A copy of this very report and the owner's manual can also be found on SharePoint in the shared folder and was uploaded by Ikponmwosa Evbayiro.

Background

Purpose

The purpose of this project is to enhance water pollution monitoring through real-time analysis. It aims to enable remote testing in shallow bodies of water using an autonomous device capable of navigating through a route determined by the user to conduct water quality measurements and determine meaningful trends and patterns from the data.

Problem

Water quality monitoring is vital for environmental health and public health. Poor water quality can have far-reaching consequences, not only affecting aquatic life but the surrounding ecosystem as well. Consequently, responsive measures are essential to dealing with issues of water pollution.

One of the ways water contaminations occurs is through the introduction of pesticides, waste, and sewage from residential and industrial areas into aquatic environments [1]. This situation is not uncommon in Houston. In 2022, Buffalo Bayou Partnership, a group dedicated to combating the recurring presence of trash in Buffalo Bayou, collected and removed more than 2000 cubic yards of trash and debris from the waterway, which is approximately equivalent to 167 commercial dump truck loads [2].

In addition to visible contamination, water quality tests have identified high concentrations of metals and nutrients in Buffalo Bayou. A study published in 2020 found that several sampling sites had nitrogen concentrations that exceeded the Texas Human Health (THH) criteria of 10 ppm for water samples [3]. The study also determined that concentrations of phosphorus, copper, arsenic, and lead exceeded the critical limits set by THH and the Environmental Protection Agency.

Our project aims to tackle the issue of water contamination in the bayou by utilizing autonomous testing. Additionally, we intend to implement an algorithm to assist in identifying potentially contaminated areas in the bayou.

To address this issue, we require an autonomous boat capable of navigating Buffalo Bayou. The boat should feature a propulsion system for effective maneuvering, debris-handling capabilities, and environmental friendliness. Additionally, it should be compact enough for single-person transportation, able to navigate narrow waterways, and be waterproof.

For complete autonomy, the boat must integrate an obstacle avoidance system for real-time hazard detection, algorithms for environmental mapping, and precise self-positioning. It should communicate with a ground control station, conduct measurements with and without user guidance, and possess decision-making capabilities to assess its ability to complete assigned missions.

The boat should be equipped with sensors to measure various water quality parameters, enabling post mission data analysis for insights into bayou contamination. The data should be presented in a user-friendly format, and the drone should have sufficient power to last the entire mission duration.

Patent Search

Table 1: Autonomous Airboat Patent Comparison

Product/ Patent No.	Team 12 – ECE 4335/6	US 11,131,995	US 2005/0016430	US 2022/0145756
Name	S.S. Autonomous Water Quality Monitor	Autonomous Aquatic Herbicide Application	Autonomous Surface Watercraft	Seafloor Harvesting with Autonomous Drone Swarms
Autonomous Navigation	X	X	X	X
GPS Integration	X	X		
Real Time Data Collection	X	X	X	X
Wireless Communication	X	X	X	
Obstacle Avoidance	X	X	X	
Remote Control	X		X	

Our prototype introduces two key innovations compared to the three patents found. Firstly, the modular water quality module enables water quality experts to obtain tailored data by facilitating the customization of sensor payloads. This flexibility ensures that the necessary parameters are measured accurately, meeting the specific requirements of each research or monitoring endeavor. Secondly, the integration of air propellers enables the boat to navigate shallow bodies of water autonomously while effectively avoiding obstacles underneath the water. Although autonomous boats for data collection and surveying are not new, the unique feature of our boat's water quality module, with its ability to change sensor payloads and acquire measurements at specific depths, distinguishes it from existing solutions.

Overview Diagram

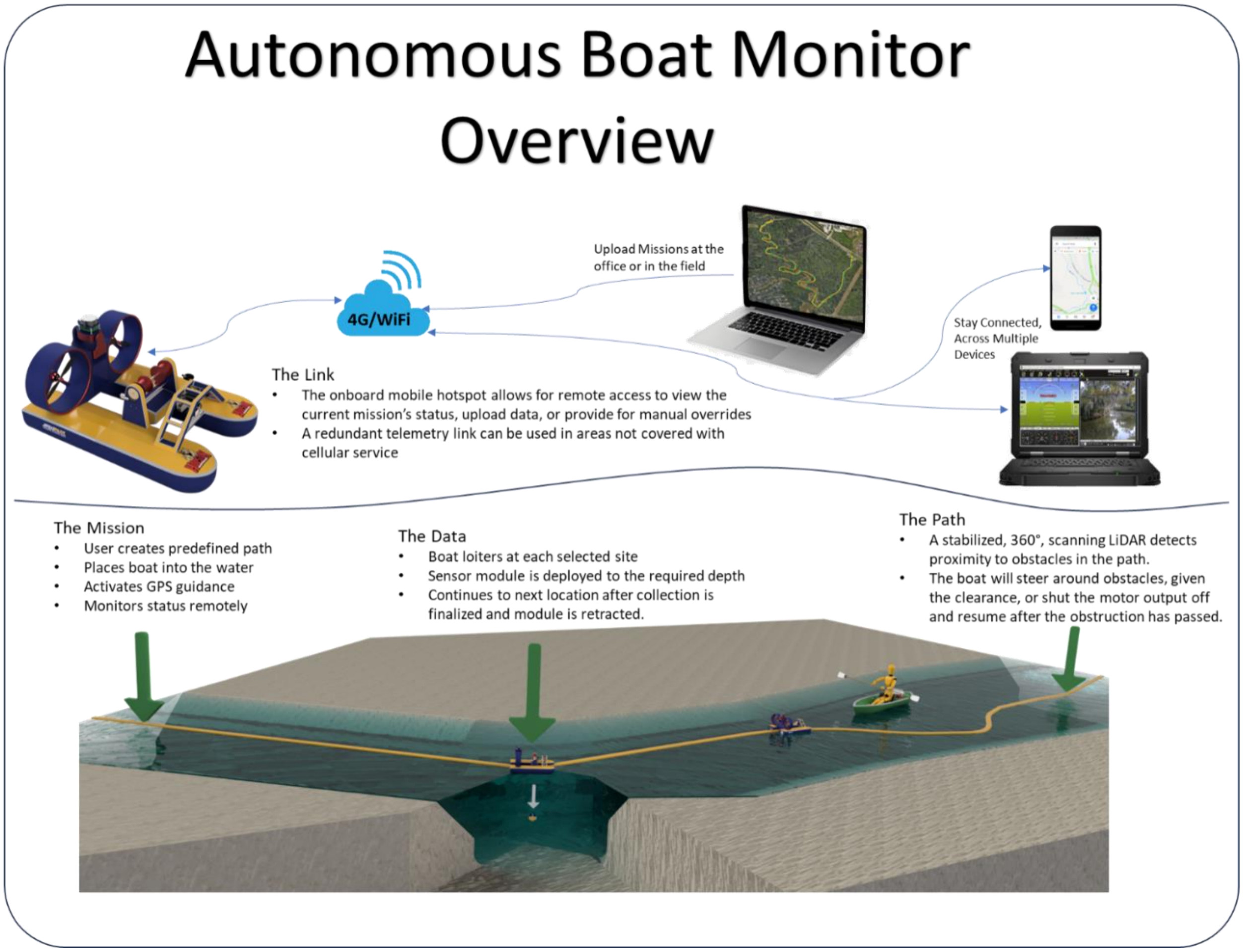

Figure 1: Autonomous Boat Monitor Overview Diagram

The airboat for the final project should be small enough to be transported by a single person, in a small boat such as the kayak shown in Figure 2; however, the actual size will only be as large as necessary to house all the components.

Figure 2 – The airboat concept (left) displayed next to a life-size dummy, kayak, and paddle (right). Currently, the bounding-box for the boat measures 35" L, 27" W, and 20" H; this represents the maximum size constraints for the final project.

To create data-collection missions, interact with the vehicle, and monitor the current mission's status, a PC with the application software will be required. Initial testing will use a telemetry modem for direct line-of-sight control, and the final project will replace this with a Raspberry Pi connected to a mobile hotspot.

Figure 3 – The airboat operator will use a PC, with the Ground Control Station Software, to create missions and monitor a current mission's progress.

The main structural and mechanical components, shown in Figure 4, will use commonly available materials and 3D printing for its manufacture. As an example: the Hull will be 3D printed in pieces; after it is assembled, it will be waterproofed with an epoxy or fiberglass layup; to seal the Cargo Bay Door to the Hull, either O-ring stock or silicone gasket can be placed along the interface.

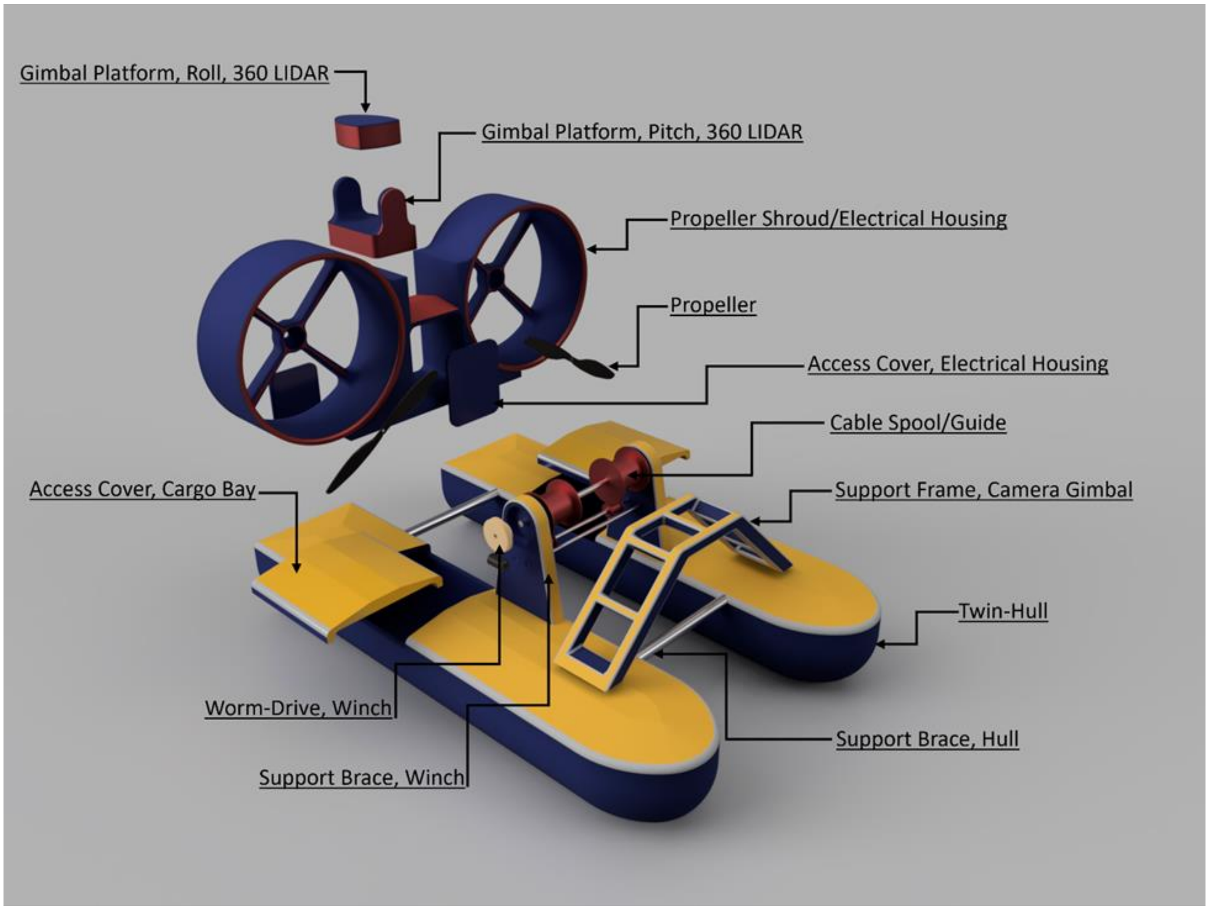

Figure 4 – The major structural and mechanical components needed for the airboat.

Figure 5 shows the main electrical components needed. The most important is the “Flight” Controller Module (FC); this is a 32-bit MCU that contains the navigation algorithms and controls all output signals to the boat’s motors and peripherals. Since it has 8 PWM outputs, 2 will be for the main motors, 2 will be for the Lidar Gimbal, 3 will be for the Camera Gimbal (unless a gimbal with a control board is used, then 2 will only be needed), and the last one will operate the winch motor. The PWM signals are sent through the Power Distribution Board (PDB), from the FC. The main motors are powered from an Electronic Speed Controller (ESC) which gets a PWM signal and converts it to a 3-phase signal for controlling the motor’s speed. The Winch Motor will also need an H-bridge driver to convert the PWM signal to power. The ESC also provides a 5 [V] output to power any servos used. The signal outputs from the flight controller. The GPS Module, Telemetry Radio, Lidar Scanner, and Raspberry Pi are directly connected to the FC.

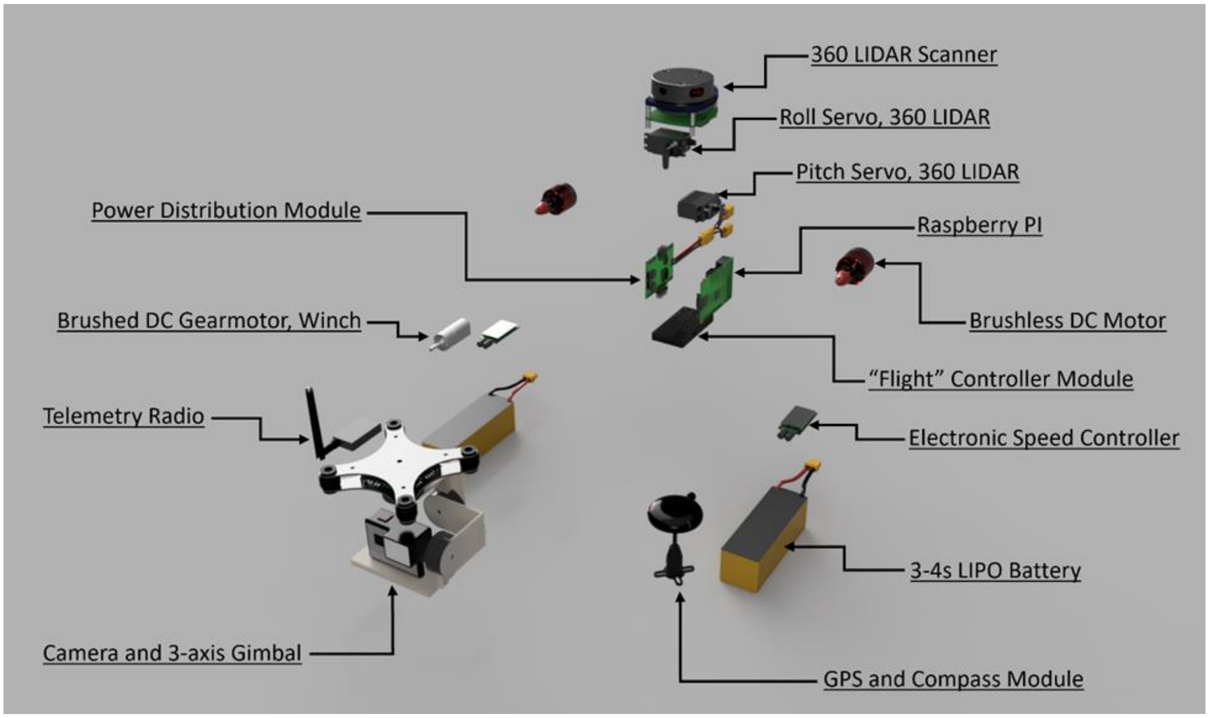

Figure 5 – The major electrical components needed for the airboat's main functionality.

The final major component is the Water Quality Module (WQM, Figure 6); this is attached to the boat by the Winch and can be lowered into the water, when commanded by the FC. For this to work, it will need to have a separate power supply and an MCU with WIFI. When the FC decides to lower the winch, it will first receive a ready signal from the Pi. The MCU will then start to monitor its sensors; because it starts off above the water, in air, a sharp change in the water quality sensor will start the logging process (steel weights will eliminate buoyancy). To know how far to lower the Winch, an ultrasonic transducer (not shown) will be mounted at the bottom of a Hull. When the WQM is back on the surface, it will send its data back to the Pi and enter standby mode. The Pi will link the WQM data to the FC data so that the date, time, location, and measurement depths can be used for further water quality analysis.

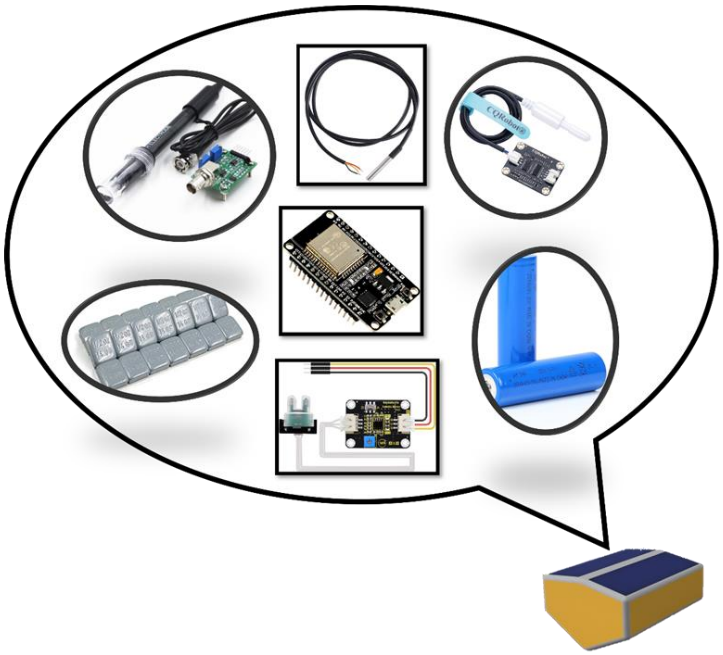

Figure 6 – The Water Quality Module will need an MCU, sensors, batteries, and weight.

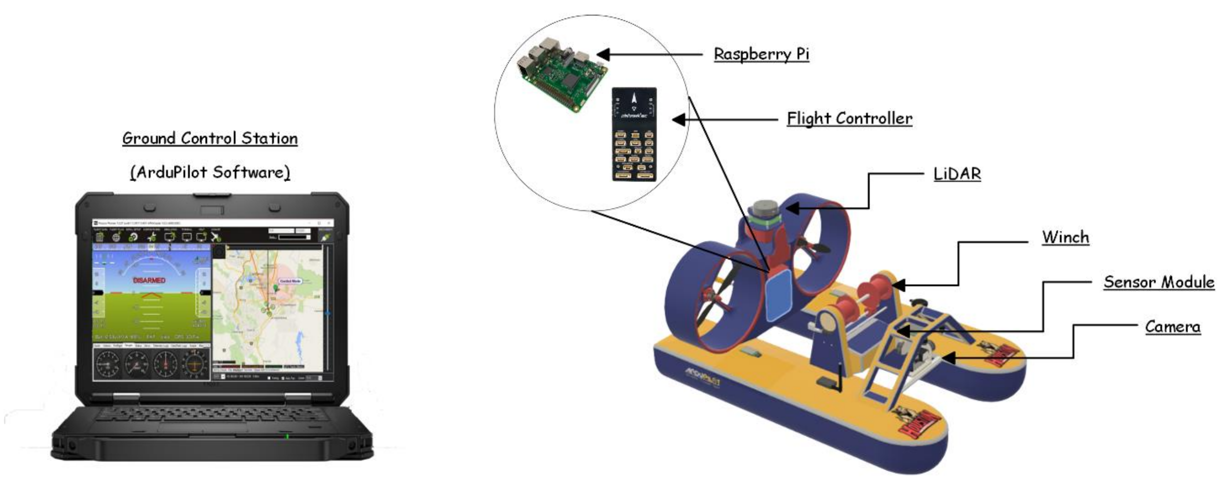

Figure 7 – The overview diagram for the Autonomous Water Quality Monitor

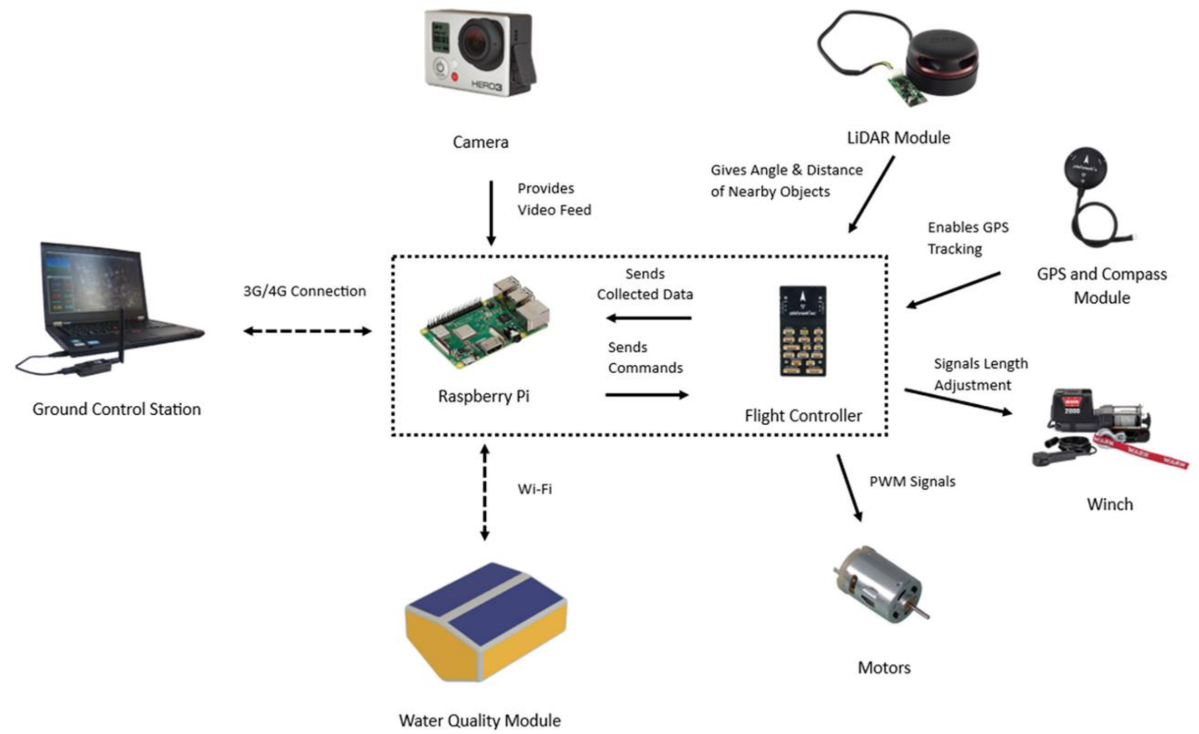

Figure 8: Autonomous Airboat Block Diagram

Figure 9: Link to full Physical Hardware Design: https://a360.co/4biV3KS

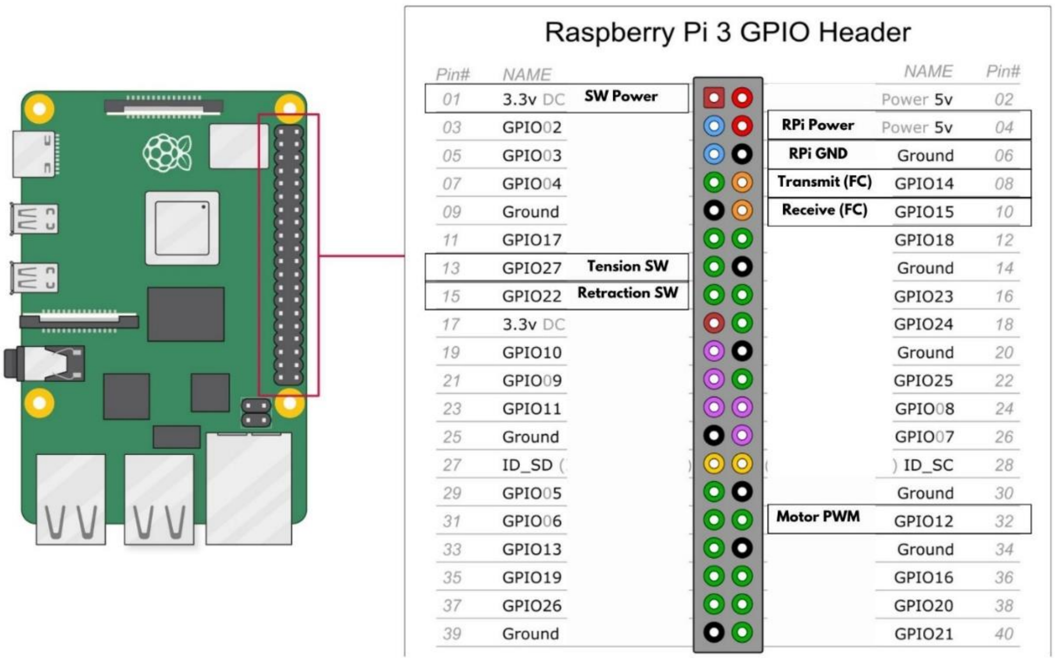

Figure 101: Raspberry Pi Pin Out

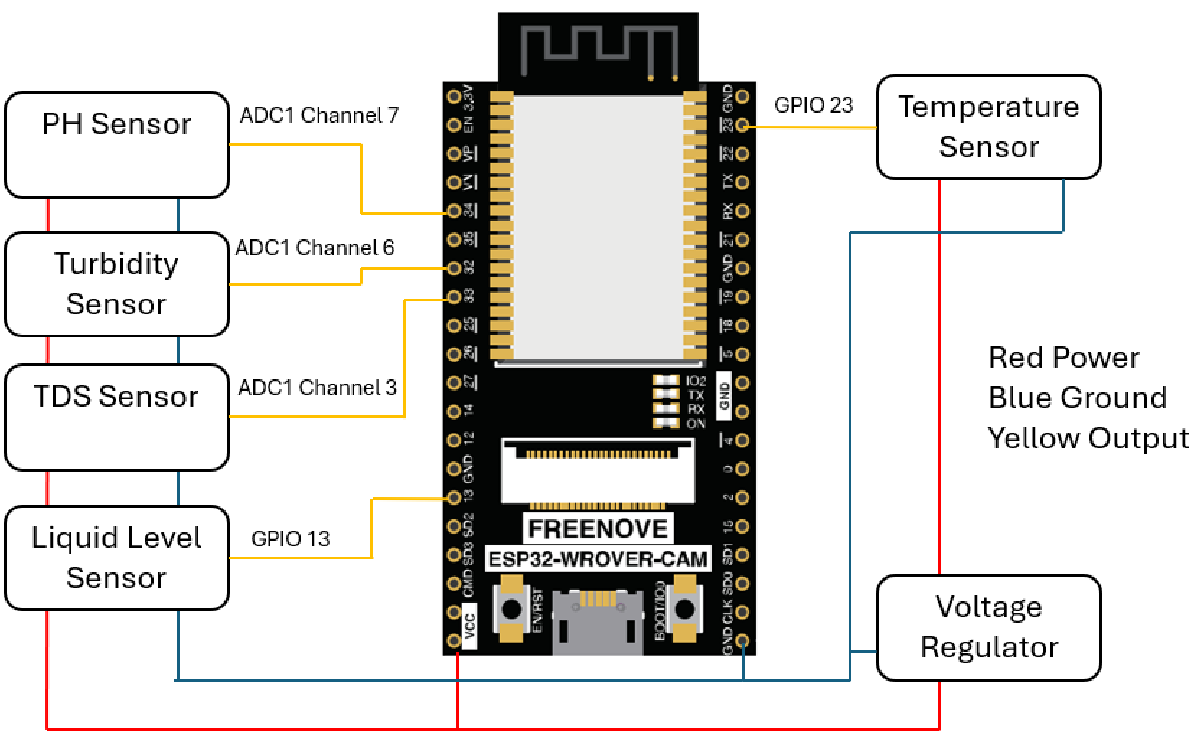

Figure 11: ESP-32 Pin Out

The software for the Raspberry Pi and the ESP-32 can be found on the team's Github Repo.

Product Specifications

- Capable of navigating shallow bodies of water
- Fully autonomous system capable of avoiding obstacles in its path.
- Remote control ability to override autonomous systems when necessary.
- For depths exceeding 3ft, measure water quality at 1ft depth; for depths under 3ft, measure at one-third of the depth.
- Able to take temperature, pH, total dissolved solids, and turbidity water quality measurements.
- Configurable water quality module to allow for integration of different sensor payloads.
- Post mission processing data tool to analyze the obtained data and identify regions of interest.

Engineering Specifications

Performance Characteristics

- Max Speed: 1.8 ±0.1 m/s (0 m/s water current)
- Cruise Speed: 1 ±0.1 m/s
- Max Pivot Turn Rate: 60 Degrees per second.

Battery Data

- Battery Life: 40 Wh
- Power Consumption (Cruise): 40 ± 2W
- Power Consumption (Idle): 3.8 ± 0.5 W

Environmental Constraints

- Max Operational Wind Speed: ≈15 MPH
- Max Opposing Water Current: ≈10 MPH
- Max Lateral Tilt: ±30^o Lateral Tilt
- Optimal Temperature Range: 40^{o}F - 110^{o}F
- Optimal in clear to minimal rain
- Not optimal in heavy fog
- Heavily cloud cover yields unreliable GPS
- Not Optimal Indoors due to signal integrity
- AVOID excessive exposure to light (3D print susceptible to be warping)
- Fog causes lidar to have less range (10m initally)

Test Plan

Our original plan was to construct the boat using 3D printed materials, which makes it unfeasible to complete bayou traversal testing by the end of the semester. However, we can proceed with testing the individual components that comprise the boat and commence programming the Raspberry Pi. This will allow us to control other components of the boat, including the flight controller and the ESP32 microcontroller. We would then test the entire system in the pond near the engineering building for full functionality checking.

Motor output test:

With propellers installed, the throttle will be set to 50% (e.g., slightly above what is needed for the nominal cruising speed), while the temperature of the motors is monitored. For any current draw, the motor temperature will increase, and using an undersized motor or improper timings will magnify this effect. For a proper setup, the motor temperatures must remain under 150 [ºF].

WQM test plan:

Each of the sensors used and the ADC that translates the readings only offer a finite resolution. The datasheets for the microcontroller and sensors typically contain this information. To know that the sensors are working properly, the collected readings, in a controlled setting, must not deviate more than the combined resolution of the sensor and ADC (Ex: if the temperature sensor readings, after going through the ADC, can offer no more than a +/- 2[ºF] resolution, but the best that we can currently measure is +/- 5 [ºF], then we must provide a +/- 5 [ºF] as our temperature-sensor-resolution, not +/- 2[ºF]). The valid measurement ranges must also be determined (e.g., 40 – 150 [ºF] for a temperature sensor).

Pi test plan:

The Pi is to be connected to a UART on the autopilot and to a local WIFI network. Using a PC also connected to that same network, a command message will be sent the Pi. The Pi will validate that this is a known command before forwarding it to the autopilot. For this to be successful, the boat must properly respond to these messages by performing an action (e.g., arm the vehicle, set the drive-mode, activate the motors, etc...).

Application test plan:

The application must display a satellite map of a region that contains the GPS coordinates of the measurements. Each GPS location of the sampled data will be marked with a dot on the map. When the user clicks on (or hovers over) a dot, the corresponding sensor measurements will be displayed. If the user searches for a sensor value within a certain range, then only the dots that have a reading within that range will be visible on the map.

AI test plan:

The AI will need to be trained on data that relates the water quality parameters to a known family of contaminates (Ex: coliforms are related to turbidity and temperature). The AI will have to detect which sampled locations contain parameters known to maximize that family's concentration so that the user application will only display those dots.

Schedule (Gantt Chart)

A snapshot of the team's progress is shown in Table 2, below. The full Gantt chart and weekly schedule can be accessed from this link:

https://uofh.sharepoint.com/:x:/r/sites/Section_H_20241_ECE_4336_12700/Shared%20Documents/Team%2012(Michael%20Stinson)/Gantt%20Chart.xlsx?d=w68ec5e6cb9b8420092cf4299de33bada&csf=1&web=1&e=BY1Ssj

Table 2: Project Task from the live Gantt Chart, updated 4/30/2024.

Owner	Task Num	Description	Progress
Michael	1.2.1	3D model a proof-of-concept	100
Michael	1.2.2	Design, print, assemble, and test the electronics housing	100
Michael	1.2.3	Design, print, assemble, and test the motor assembly	100
Michael	1.2.3	Design, print, assemble, and test the hull assembly	100
Michael	1.2.4	Design, print, assemble, and test a lidar gimbal	100
Michael	1.2.5	Design, print, assemble, and test the WQM housing and winching system	100
Michael	1.3.1	Install Ardupilot firmware	100
Michael	1.3.2	Configure motor and servo output	100
Michael	1.3.3	Tune the PID loops for each flight mode	100
Michael	1.4.1	Configure UART on FC to work with the SiK module	100
Michael	1.4.2	Connect the FC to PC application over telem link	100
Michael	1.4.3	Configure UART on FC to accept the CRSF protocol over serial	100
Michael	1.4.4	Flash EdgeTX firmware to the RC transmitter, bind to and update the reciever	100

Michae l	1.4.5	Setup all controllable outputs and necessary flight modes	100
Michae l	1.4.6	Install and verify the failsafe action for the map-viwewer LUA script	100
Michae l	1.5.1	Flash latest BLHeli_S firmware to salvaged ESCs	100
Michae l	1.5.2	Configure FC to output Bi-Directional D-Shot prtotcol thru the FMU/PWM output	100
Michae l	1.5.3	Connect ESCs to PDB and verify the forward and reverse thrust	100
Michae l	1.6.1	Verify the raw output from lidar module with a PC application	100
Michae l	1.6.2	Configure the spare UART on the FC and verify connection to lidar	100
Michae l	1.6.3	Configure gimbal servo output to maintain a level attitude with the horizon	100
Michae l	1.7.1	Calibrate compass and IMU sensors	100
Michae l	1.8.1	Configure gimbal servo output to maintain a level attitude	100
Michae l	1.8.2	Configure yaw axis to be user set	100
Michae l	1.9.1	Deburr and fit-check all items	100
Michae l	1.9.2	Sand and epoxy coat all exposed parts	100
Michae l	1.9.3	Preinstall all cables and determine the proper wiring layout	100
Michae l	1.9.4	Apply and verify all seals are watertight	100
Michae l	1.10.1	All systems perform as expected on the ground	100
Michae l	1.10.2	Vehicle can complete a navigation only mission	100
Michae l	1.10.3	Vehicle avoids obstacles durring a mission	50
Michae l	1.10.4	Vehicle performs a successful mission in a shallow bodies of water	100

Fredy & Ike	2.1.1	Connect raspberry pi to drone engage web client	100
Fredy & Ike	2.1.2	Connect raspberry pi to Pixhawk through UART for drone engage	100
Ike	2.1.3	Connect raspberry pi to camera and select camera resolution	100
Fredy & Ike	2.1.4	Test remote control ability	100
Fredy & Ike	2.2.1	Connect raspberrpi to Pixhawk through UART for dronekit	100
Fredy	2.2.2	Send and receive messages to Pixhawk with dronekit	90
Fredy	2.3.1	Create a serial splitter to allow for Drone Enage and Dronekit to use the same uart	100
Ike	2.4.1	Rotate stepper motor clockwise and counterclockwise	100
Ike	2.4.2	Control RPM of stepper motor	100
Ike	2.4.3	Write spiral winch control function for WQM descent	100
Fredy & Ike	2.5.1	Create an autunomous loiter mode & a manual mode	100
Daniel	3.1.1	Determine framework/environment best suited for the ESP’s purpose	100
Daniel	3.1.2	Flash firmware to ESP32	100
Daniel	3.1.3	Setup RTOS	100
Chima	3.2.1	Integrate DS18B20 library for digital sensor into Espressif	100
Chima	3.2.2	Determine the precision of the sensor	100
Chima	3.3.1	Create/find code suitable for obtaining turbidity measurements	100
Chima	3.3.2	Verify the sensor functions appropriately	100
Chima	3.4.1	Integrate Arduino reference code into Espressif	100
Chima	3.4.2	Verify the sensor functions appropriately	100
Chima	3.5.1	Integrate DFRobot_ESP_PH library for sensor into Espressif	100
Chima	3.5.2	Calibrate sensor	100
Daniel	3.6.1	Create socket server using ESP32	100
Danil & Chima	3.6.2	Send data through socket server	100
Daniel, Chima,	3.6.3	Connect Raspberry Pi to ESP32 through socket server	100

Fredy, & Ike			
Daniel, Chima, Fredy, & Ike	3.6.4	Simulate WQM data collection in lab	100
Daniel, Chima, Fredy, & Ike	3.6.5	Simulate WQM data collection with WQM submerged in water	100
Fredy	4.1.1	Generate fake data to emulate mission data results	100
Daniel	4.1.2	Select sensitivity for the decision making tree algorithm	100
Daniel & Fredy	4.2.1	Generate 2d-plot & 3d-plots of to analyze mission data	100
Daniel & Fredy	4.3.1	Create a user interface to display 2d-plots, 3d-plots, and decision making tree algorithm results	100

Risk Management

Table 3. Original Risk Assessment Matrix

			1.10.2a		
	2.1.4 & 2.2.2a		2.1.4, 2.2.2, & 3.6.3a	2.1.4a 2.1.4, 2.2.2, & 3.6.3b	
	3.5.2a	1.10.3a			
				1.2.4a	

Severity					
Probability					

Table 2. Original Risk Mitigation Actions

Task Number	Risk	Risk Mitigation	Severity	Probability
2.1.4a	Latency too high on mobile hotspot	1. Decrease camera resolution and frame rate	3	4
2.1.4, 2.2.2, & 3.6.3a	Drone Engage remote control, Dronekit control, and Raspberry Pi & ESP 32 Communication. One application bottlenecking the system data transfer	1. Create an Exception handler to handle bottleneck	4	3
2.1.4, 2.2.2, & 3.6.3b	Drone Engage remote control, DroneKit control, and Raspberry Pi & ESP 32 Communication. Mobile hotspot connectivity issues	1. Develop an android app to manage the mobile hotspot connectivity of the systems	4	4
2.1.4 & 2.2.2a	Drone Engage and Dronekit Mavlink messages sending at the same time	1. Test sending Mavlink messages with both applications to the flight controller	4	1

3.5.2a	PH sensor precision degrades over time	1. Resolve the error with the two-point calibration method provided by DFRobot 2. Create calibration method	1	3
1.10.2a	Cannot complete mission, too little buoyancy	1. Add "foam" to outer hull to increase the payload capacity	5	3
1.10.3a	LiDAR works unexpectedly, cannot avoid obstacles	1. Tune/filter FC data. 2. HW redesign. 3. Change scope	3	2
1.2.4a	LiDAR gimbal incomplete	. 1. Modify or use the old version instead.	2	4

After performing our original risk assessment our four predicted risk were:

1. 1.10.2a cannot complete mission because of lack of buoyancy
2. 2.1.4a Mobile hotspot latency too high
3. 2.1.4,2.2.2&3.6.3a Drone Engage remote control, Dronekit control, and Raspberry Pi & ESP 32 communication. One application bottlenecking the system data transfer
4. 2.1.4,2.2.2&3.6.3b Drone Engage remote control, Dronekit control, and Raspberry Pi & ESP 32 communication. Mobile hotspot connectivity issues

Our risk mitigation plan for task 1.10.2a successfully allowed us to drive the boat with the additional weight of the water quality module. For the risk mitigation plan associated with task 2.1.4, 2.2.2, and 3.63, we were not able to implement the risk mitigation due to the team not having android app development experience. Because of this the product specifications were changed from remote control access anywhere with telephone service, to line of site remote control. Lastly, an unexpected risk was the risk of integrating all the induvial software subsystem together. This oversight in expecting issues led to the boat software subsystems working individually but not all cohesively. Table n displays the final risk assessment matrix.

Table n. Final Risk Assessment Matrix

					2.1.4, 2.2.2, & 3.6.3
	2.1.4 & 2.2.2a		2.1.4, 2.2.2, & 3.6.3a		
	3.5.2a	1.10.3a			
				1.2.4a	
Severity			1.10.2a		
Probability					

Accomplishments

Prototype Demos

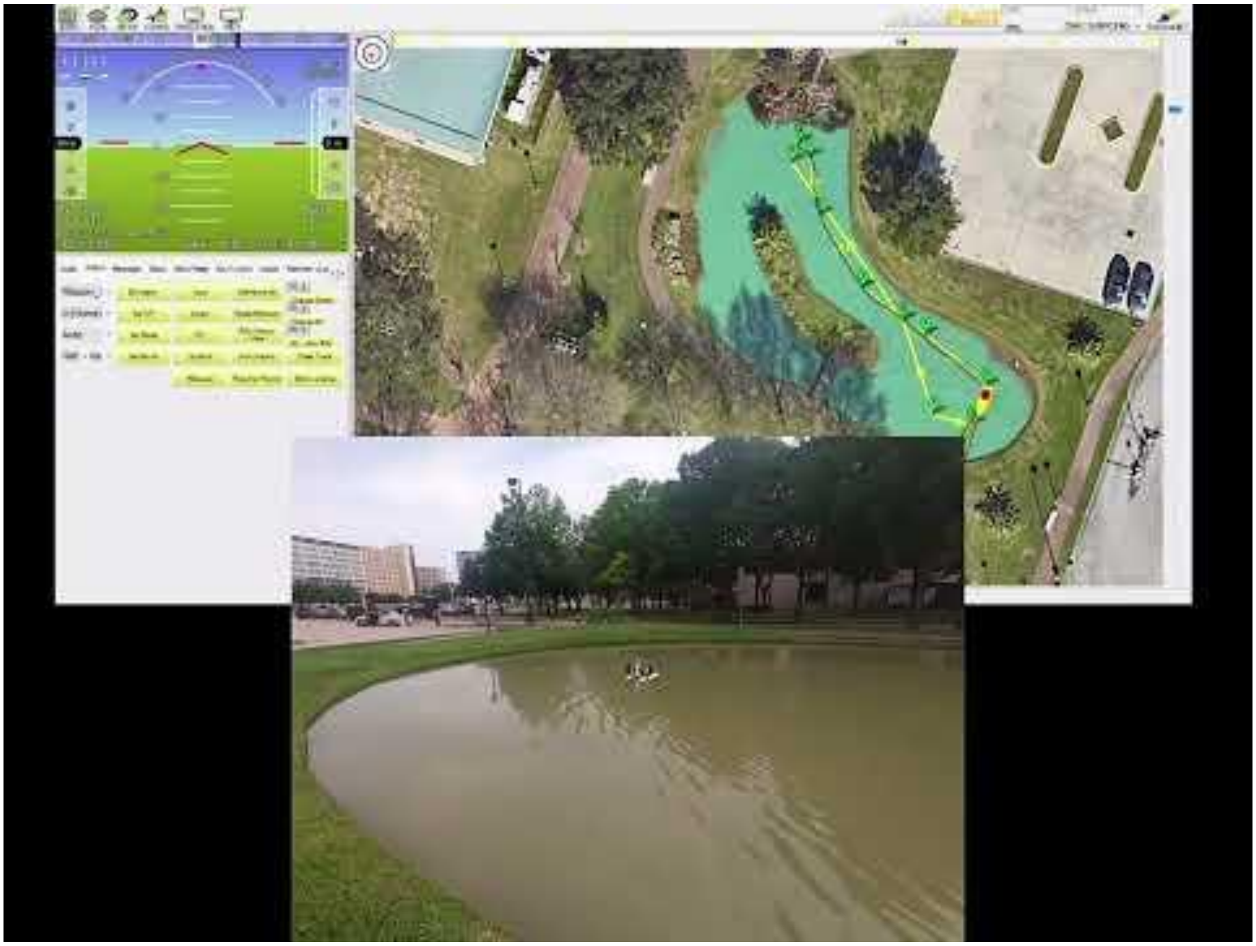

Figure 12: Demo of Boat Navigation

Figure 13: Water quality module descent and ascent demo

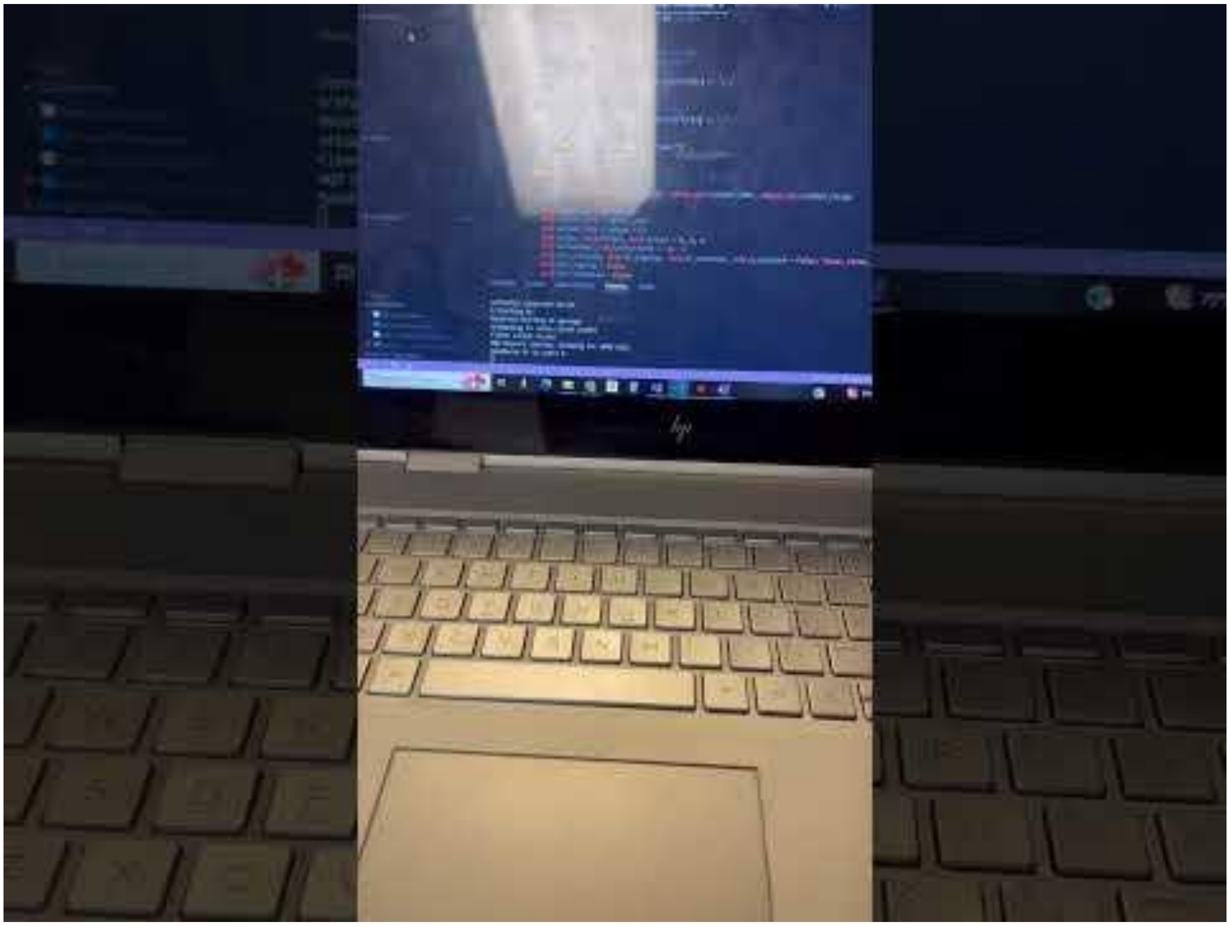

Figure 14: WQM Sensor Reading

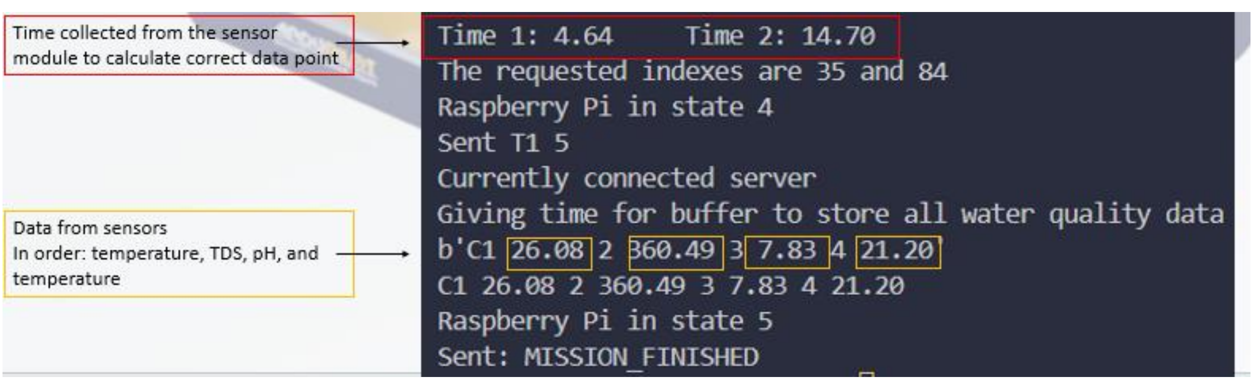

Figure 2: WQM Sensor Readings Explained

The autonomous airboat project has given us a significant opportunity to learn so much regarding the bring up process for a system/device. We successfully had a fully integrated prototype that although didn't work during integration, each subsystem worked stand alone. This is something to be proud of due to the project turning from if it'll work to when it could work. We successfully controlled the boat autonomously and with user control from a remote controller. Our project was able to deploy the water quality module with parameters to be undeployed, while also being able to get data from this water quality module with different sensors. We were also able to implement an anomaly detection algorithm to determine points of interest.

From this project we learned the importance of project management, being able to effectively have team meetings, track team progress, and assess certain product features for their likelihood of implementation. Our team had a few parts of the project that needed to be overhauled, such as the camera due to overambition with our skillsets, unforeseen issues, and lack of funds. This allows us within future research, companies, or contract work to properly run a team or be a part of a team better than we could before we took the project on.

Reflecting on the products performance, our team recommends investigating alternative hull materials and a larger hull design for better center of gravity, along with better buoyance. One could potentially integrate additional sensors, or even make the payload something different as a watercraft is very versatile in use. By addressing these recommendations and continuing to work diligently, the team is confident that the autonomous airboat project will make a significant impact on the health of Houston water quality or any field it is applied too for that matter.

Disclosure

Acknowledgements

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References

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[2]“Waterway Cleanup – Buffalo Bayou Partnership.” https://www.buffalobayou.org/our-work/waterway-cleanup/ (accessed Nov. 05, 2023).

[3] T. Bukunmi-Omidiran and B. B. Maruthi Sridhar, “Evaluation of spatial and temporal water and soil quality in the Buffalo and Brays Bayou watersheds of Houston, Texas,” Remote Sensing Applications: Society and Environment, vol. 21, p. 100455, Jan. 2021, doi: https://doi.org/10.1016/j.rsase.2020.100455.

[4] Link to the interactive 3D conceptual Model - https://a360.co/45iW1mN

[5] The “flight” controller’s reference wiki - https://ardupilot.org/rover/index.html

[6] Comprehensive methods for water quality sampling and measuring - https://www.hach.com/resources/water-analysis-handbook?origin=dropdown&c1=support&c2=information-center&c3=water-analysis-handbook-wah&clickedon=water-analysis-handbook-wah

[7] National Field Manual for the Collection of Water-Quality Data - https://www.usgs.gov/mission-areas/water-resources/science/national-field-manual-collection-water-quality-data-nfm