SANTA CLARA UNIVERSITY

Department of Computer Science and Engineering
Department of Electrical and Computer Engineering
Department of Mechanical Engineering

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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ENTITLED

MANTARAY Profiler

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREES OF

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MANTARAY Profiler

by

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SENIOR DESIGN PROJECT REPORT

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Department of Electrical and Computer Engineering
Department of Mechanical Engineering

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Abstract

Ocean health monitoring is essential for understanding and protecting marine ecosystems, yet existing methods of collecting oceanographic data are often expensive, labor-intensive, and difficult to scale. This project presents the design, integration, and testing of the MANTARAY Profiler, a low-cost, autonomous ocean-monitoring system developed to support repeatable environmental data-collection missions with reduced operator involvement. The system was designed to navigate among multiple surface waypoints, execute vertical profiling maneuvers, and collect water-column data while maintaining a compact, user-friendly, and transportable platform.

The profiler travels horizontally across the water surface to a predetermined GPS waypoint using autonomous navigation and heading-control algorithms. Once the waypoint is reached, the vehicle transitions from a horizontal orientation to a vertical profiling position through an internal buoyancy-shifting mechanism that changes the relationship between the center of mass and the center of buoyancy. In the vertical state, the profiler is designed to perform a controlled dive to depths of up to 30 meters while collecting environmental data, including dissolved oxygen, pH, conductivity, temperature, and depth measurements throughout the water column. After resurfacing, the profiler is intended to reorient itself to its horizontal configuration and travel to the next waypoint, repeating the process for multiple dives spaced approximately 100 meters apart.

The project integrated several interdisciplinary subsystems, including structural and mechanical design, autonomous navigation and control, wireless communications, onboard computing, environmental sensing, power distribution, and health monitoring. A dual-microcontroller architecture coordinated mission execution, waypoint navigation, sensor collection, and actuator control, while a graphical user interface allowed operators to configure missions, monitor system status, and visualize collected data. Subsystem and preliminary integration testing demonstrated successful communication between subsystems, autonomous navigation behavior under controlled dry-test conditions, vertical orientation transitions, and environmental sensor functionality. Overall, the MANTARAY Profiler demonstrates the feasibility of a low-cost autonomous marine vehicle architecture capable of supporting future repeatable oceanographic monitoring missions and expanding accessibility to environmental data collection.

Keywords: Autonomous Underwater Vehicle (AUV), Ocean Monitoring, Environmental Data Collection, GPS Navigation, Marine Robotics, Water Quality Sensors

Acknowledgements

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We would also like to thank our advisors and mentors, Dr. Christopher Kitts, Dr. Michael Neumann, and Dr. Sally Wood, for their guidance, technical feedback, and encouragement throughout the development process. Their experience and advice helped our team make important design decisions, overcome technical challenges, and stay focused on the project goals.

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Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

This chapter introduces the motivation behind the MANTARAY Profiler and explains the need for a low-cost autonomous ocean-monitoring system. It discusses the limitations of existing data collection methods, reviews relevant background research, and summarizes the customer and stakeholder needs that guided the project requirements.

1.1 Motivation

The ocean underpins climate regulation, marine ecosystems, and coastal economies, yet it remains significantly undersampled, especially for biogeochemistry and in regions that are costly or hazardous to reach. Traditional conductivity, temperature, and depth (CTD) sensors used on research vessels, along with diver-deployed instruments, provide high-quality data but are expensive, logistically complex, and limited in temporal and spatial coverage. Emerging ocean industries, including offshore energy, seabed mining, marine aquaculture, and coastal infrastructure, are pushing operations into deeper, more energetic, and more environmentally sensitive waters. These sectors require more continuous, higher-quality data on temperature, salinity, dissolved oxygen, and related variables to support safe operations and environmental stewardship.

Recent reviews of ocean engineering note that oil and gas technologies have laid the foundation for growth in other ocean sectors, but that this growth is contingent on strict environmental protections and improved monitoring capabilities. This, in turn, drives demand for networked marine systems, autonomous platforms, and robust, scalable sensing architectures [13]. Low-cost, reliable profilers that can repeatedly sample the water column without a full research vessel are a key piece of that monitoring puzzle.

At the same time, global observing programs such as Biogeochemical-Argo (BGC-Argo) have demonstrated the transformative impact of autonomous profiling floats. These systems deliver routine, vertically resolved measurements with rapid public data release, feeding directly into climate and ecosystem science [9]. However, most Argo-class floats are optimized for deep-ocean environments and are not well suited to near-shore, surf, glacier-front, or harbor operations, where water depths are shallower, topography is more complex, and deployment opportunities are more constrained [9] [10].

This project targets that gap. The "Profiler" system is conceived as a small autonomous waypoint profiler that can execute repeated vertical profiles and short horizontal transits in coastal and near-shore environments, with a focus on safety, low operational overhead, and student-lab-scale cost. The goal is to give applied scientists and field researchers a practical alternative to divers, large Autonomous Underwater Vehicles (AUVs), and expensive ship time for routine water-column surveys.

1.2 Background and Research

Various solutions already exist regarding ocean health monitoring systems, including: Divers, Remotely Operated Vehicles (ROVs), and AUVs. On a reef in Lake Tahoe, scientists send divers for about one week each year to collect data that these robots aim to gather. While this solution works, it limits the amount of data that can be collected and can be quite expensive to hire. Similarly, existing ROVs and AUVs are great because they are not time-limited; however, they are extremely costly, and independent researchers will not be able to afford them.

Santa Clara University's (SCU) Robotics Systems Laboratory (RSL) also has a strong history in marine robotics and has worked with a wide range of scientists, companies, and agencies. Over the years, the lab has developed and supported various underwater robotic systems, including rovers, remotely operated vehicles, autonomous underwater vehicles, and earlier profiler designs.

These systems have supported ocean and water-column research in various ways. The profiler work is especially important for our project because MANTARAY builds on that existing foundation.

One previous RSL design to note was the Vertical Profiler. The vertical profiler was designed to collect data at user-defined depths and is in excellent working condition. It was especially valuable because it showed that a lower-cost student-built profiler could collect water-column data without needing a large commercial AUV. It is much smaller than many research-grade systems and was designed around modular scientific sensing, allowing it to be transported by one person, which is useful for ocean monitoring. A CAD model and physical build of the vertical profiler is seen in Figure 1.1 However, there were still limitations. The previous system focused on moving up and down through the water column, collecting data at different depths, and returning to the surface. To move the vertical profiler to another

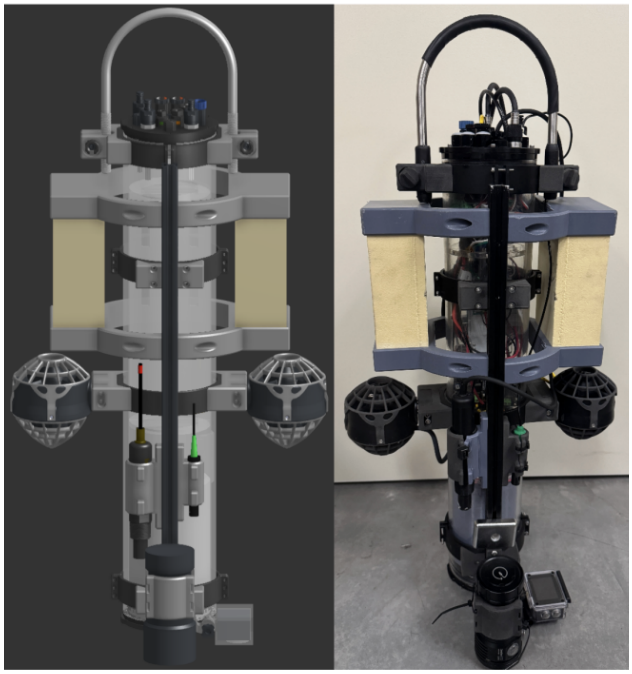

Figure 1.1: CAD of Existing Vertical Profiler - Courtesy of the Robotics Systems Laboratory at Santa Clara University [1].

location, it would have to be transported by boat each time, which could add further expenses and complexity.

1.3 Customer and Stakeholder Needs

The vertical profiler was our main starting point with our stakeholders. The existing profilers work beautifully and remain in use, but our stakeholders, including scientists and RSL staff, have an overwhelming need for automated, repeatable dives.

After conducting a variety of interviews, we found the following common themes among our stakeholders: reliable data, ease of use for non-engineers, extended power capabilities, surface navigation, and ease of maintenance.

- Reliable Data: Dr. Williams mentioned having a simpler profiler, but reliable data is more important than "feature-creep" without the data that makes it useful.
- Easy for non-engineers to use: Dr. Kitts mentioned that it's crucial we design with accessibility in mind because not every customer necessarily has an engineering background. As a result, it should be a system that someone can easily be trained to use.
- Extended Power Capabilities: Multiple interviewees noted that it would need to last for various hours to be useful in a deployment where a scientist does not need to worry about constantly switching out the batteries.

- Surface Navigation: All interviewees agreed that a major feature they would like to see implemented in this system was surface navigation. Rather than going out on the water themselves, they would prefer to have the system deployed from shore after setting the locations.

- Ease of Maintenance: Dr. Kitts and Dr. Neumann touched on the need for easy maintenance so the system can be repaired during deployment or worked on by future students to keep the system running when we are not there anymore.

Chapter 2

System Description

This chapter defines the overall system goals, requirements, and operating concept for the MANTARAY Profiler. It explains the intended mission sequence, identifies the major system requirements, and describes how the profiler is divided into subsystems that work together to support autonomous navigation, data collection, and recovery.

2.1 Project Statement

The project mission of this project is to develop a low-cost AUV-based ocean health monitoring system capable of monitoring columns of water at predetermined waypoints across a body of water. This AUV will hit these waypoints horizontally, cover a distance of at least 100m, and traverse vertically to a minimum depth of 30m, collecting CTD and additional science sensor data. This includes conductivity, temperature, depth, pH, and dissolved oxygen measurements from the scientific sensor suite. The scope of the project is to deploy the profiler from shore, configure a predetermined mission, and then let the profiler go. The profiler will then be collected after its mission is accomplished. CTD and additional science sensor data will be collected during the mission and downloaded after the mission is completed. One of this profiler's key features is its ability to traverse horizontally and vertically. The actuation process is a key challenge that our team solved through the implementation of the lead screw, moving buoyancy foam. To ensure our profiler can localize different waypoints within a 5-meter radius, a GPS navigation system will be integrated into the profiler. This system will ensure that it arrives at the correct waypoint locations.

2.2 Concept of Operations

Our concept of operations begins with the profiler being deployed from the shore in its horizontal orientation, as illustrated by the first step in Figure 2.1. Before deployment, the operator uploads the mission parameters via the graphical user interface, including waypoint locations and the desired dive depth. Once powered on and placed in the water, the profiler initializes its sensors and uses the GPS system to determine its current position relative to the programmed waypoints.

The profiler then begins autonomous navigation toward the first waypoint using its thrusters and heading control algorithms. As shown in step 2, the navigation system continuously calculates the bearing and distance to the target waypoint while correcting its heading in real time. Once the profiler reaches the acceptable waypoint error range, it transitions to the dive state.

To begin the dive sequence, the profiler changes from a horizontal to a vertical orientation through its buoyancy-shifting mechanism. Two servo motors drive a lead screw system that moves the buoyancy foam along the profiler's body, intentionally shifting the relationship between the center of mass and the center of buoyancy. This creates a moment arm that rotates the profiler into its vertical orientation.

After reaching vertical equilibrium, shown in step 3, the thrusters drive the profiler downward toward the desired depth. During descent, the scientific sensor suite continuously samples water column data, including pH, dissolved oxygen, conductivity, temperature, and depth. A first Arduino collects and formats this sensor data, while a secondary one logs the mission state and position.

Once the profiler reaches the target depth in step 4, the thrusters shut off, and the vehicle returns to the surface using its positive buoyancy. While ascending, the profiler continues collecting sensor measurements to create a complete vertical profile of the water column, as shown in step 5.

After resurfacing, the GPS system reacquires the profiler's position and computes the trajectory to the next waypoint. The profiler then repeats the navigation, flipping, diving, and data collection process for each programmed waypoint in the mission. After completing all dives, the profiler autonomously returns to the original deployment location on shore, as shown in step 6, where the operator can download and analyze the mission data.

2.3 System Requirements

By understanding our customers' needs, we determined the requirements for our system. The requirements were broken down into two categories: enhanced science missions and operational efficiency. The enhanced science mission category was the feature our scientists cared about most. Operational efficiency was among the RSL stakeholders' requirements to ensure a reliable, working system.

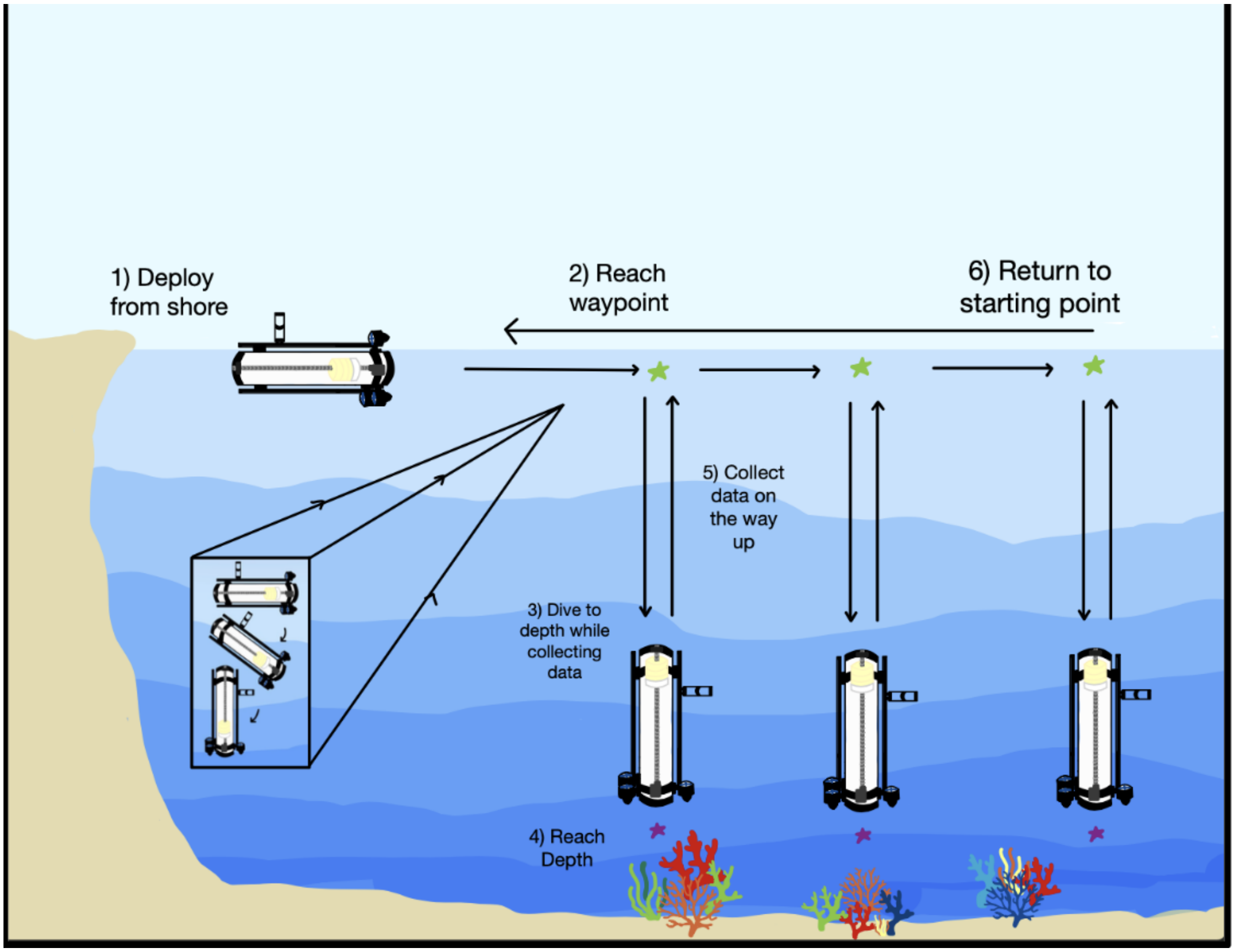

Figure 2.1: Concept of Operations

Enhanced Science Missions:

- Dives: Must make a minimum of 3 dives.
- Navigation: Must be able to autonomously travel to waypoints.
- Distance: Must be able to dive to a depth of at least 30 meters and travel 100 meters between waypoints.
- Scientific Sensors: Must be equipped with the following sensors: Dissolved Oxygen, Depth, pH, Temperature, Conductivity

Operational Efficiency:

- Buoyancy: Must be positively buoyant between 1 and 5 Newtons.
- Orientation/Pitch: Must be within ± 20° vertical and ± 30° horizontal.

- Wireless Communication: Must be able to wirelessly upload mission parameters and receive mission data back.
- Weight: Must be under 50 pounds that 1 person can carry.
- Operator Interface: Must be user-friendly and capable of formatting data.

2.4 General System Description

The general system description of the profiler is summarized in the component block diagram shown in Figure 2.2. The system is built around two microcontrollers, shown in green, which act as the brains of the profiler. We chose a dual-microcontroller architecture to separate the navigation and scientific sensing tasks, thereby improving reliability and processing efficiency. The Arduino GIGA R1 WiFi handles the navigation and autonomy functions, including waypoint calculations, heading control, and communication with the operator interface. The Arduino Mega 2560 is dedicated to collecting, processing, and storing the scientific sensor data during the mission.

An off-board laptop serves as the operator interface before and after deployment. Prior to the mission, the laptop uploads waypoint coordinates and mission parameters to the profiler via Bluetooth using the Arduino GIGA R1 WiFi. After mission completion, the laptop receives and stores the collected mission data for analysis. Bluetooth communication is limited to short range, typically within 5 feet of the profiler.

The profiler's navigation subsystem, shown in purple, consists of the GPS module, GPS antenna, IMU, and depth sensor. The GPS system determines the profiler's surface position and assists with autonomous waypoint navigation. The IMU provides heading and orientation information, allowing the profiler to maintain the correct direction while traveling between waypoints. The depth sensor measures the profiler's vertical position in the water column during dives and ascents.

The scientific sensing subsystem, shown in blue, consists of dissolved oxygen, pH, and temperature, and electrical conductivity sensors. These sensors were selected based on stakeholder and researcher feedback to provide important indicators of ocean health and water quality. During operation, the scientific sensor Arduino continuously samples, formats, and logs sensor data.

The mechanical movement subsystem, shown in yellow, includes the three thrusters, electronic speed controllers (ESCs), and two servo motors. The thrusters provide propulsion and maneuverability for autonomous navigation, while the ESCs receive PWM control signals from the navigation Arduino to regulate thruster speed. The two servos actuate the lead screw mechanism that shifts the buoyancy foam and transitions the profiler between horizontal and vertical orientations.

The status monitoring subsystem, shown in orange, includes four LEDs and an internal leak sensor. The LEDs provide visual feedback on profiler operation and mission state, while the leak sensor detects water inside the electronics enclosure, helping protect sensitive components during testing and deployment.

Finally, the power subsystem, shown in red, uses a dual battery configuration to separate high-power propulsion loads from sensitive electronics. One battery powers the thrusters through the ESCs, while the second battery powers the microcontrollers, sensors, and servos. Two buck converters regulate the voltage supplied to the electronics, providing 5V to the Arduinos and 7V to the servo motors. Since the thrusters operate directly from the battery voltage, no voltage conversion is required for the propulsion system.

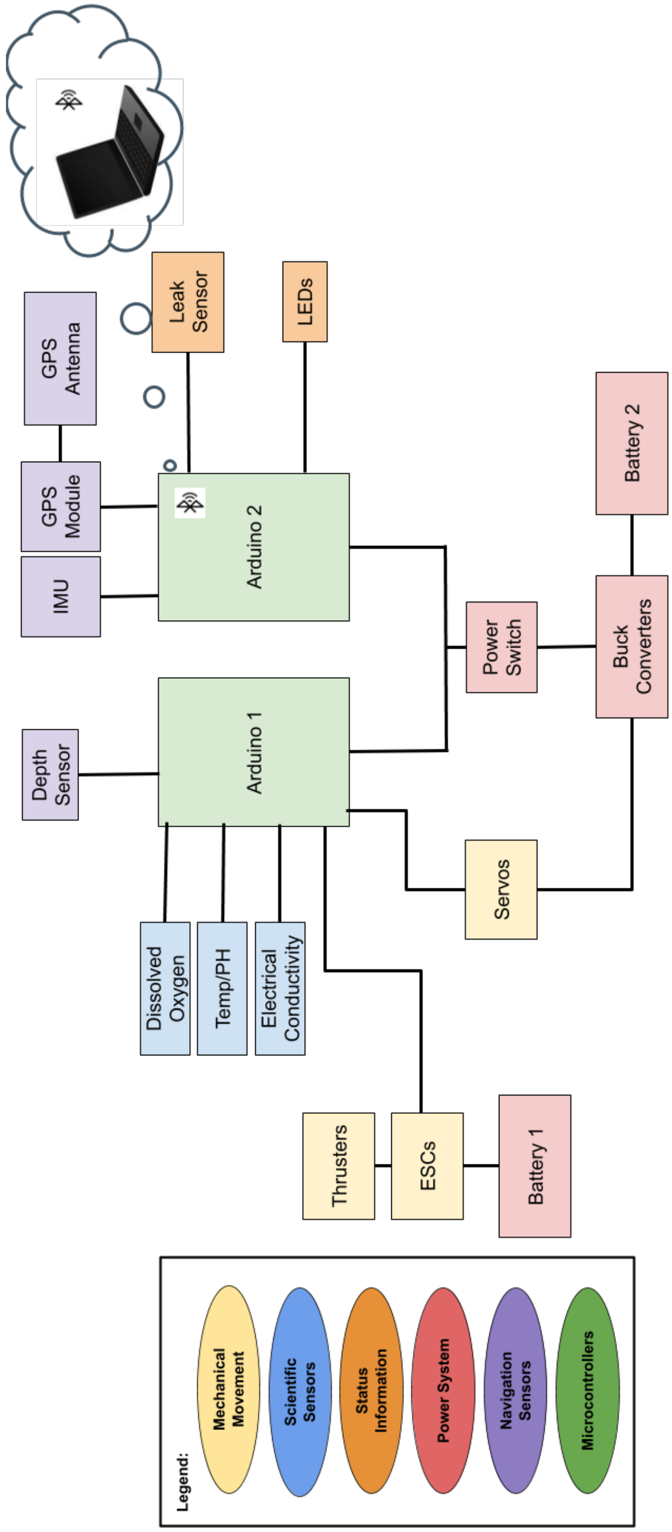

Figure 2.2: Component Block Diagram

Chapter 3

Project Timeline and Team Management

This chapter describes the project management process used throughout the development of the MANTARAY Profiler. It includes the project timeline, budget considerations, safety and risk management planning, and team allocation. These elements helped organize the project and support progress across the mechanical, electrical, software, and testing tasks.

3.1 Timeline

The development timeline for the Autonomous Vertical Profiler project consisted of multiple stages, including conceptual design, subsystem integration, mechanical testing, software development, navigation validation, and final system testing. The project was developed iteratively, with repeated cycles of testing and redesign to improve system reliability and performance. Figure 3.1 shows our project timeline.

During the early stages of development, the team focused on defining system requirements, researching underwater profiling systems, and creating the initial mechanical and electrical architecture. Initial work included the design of the pressure housing, buoyancy system, propulsion-mounting structure, and the integration of waterproof electronics.

Once the initial mechanical prototype was completed, the project transitioned into subsystem testing and integration. A major portion of the development process involved repeated testing of the flipping mechanism. Since the profiler was required to transition between horizontal and vertical orientations, extensive testing was performed to validate the reliability of the flipping subsystem.

Initial flipping tests were conducted as dry tests outside of water to verify servo timing, lead screw motion, and structural stability. These dry tests allowed the team to identify alignment issues, improve component mounting, and verify that the system could consistently rotate between orientations without mechanical interference.

After successful dry testing, the flipping mechanism was tested in a pool environment to evaluate real-world underwater behavior. Multiple iterations of pool testing were required to adjust the buoyancy distribution, improve rotational stability, and ensure the profiler could reliably transition between orientations while floating. These tests also allowed the team to evaluate waterproofing performance and propulsion behavior under water conditions.

The testing process was highly iterative. Following each round of testing, the team analyzed failures and implemented design improvements before repeating additional validation tests. This iterative process significantly improved the reliability of the flipping subsystem and allowed the team to refine the mechanical and control systems before full deployment testing.

In parallel with the mechanical testing process, software integration and navigation development were performed. Additional time was allocated toward debugging subsystem communication, validating sensor interfaces, and integrating autonomous control functionality.

The final stages of the project focused on full system integration, documentation, thesis preparation, and presentation development.

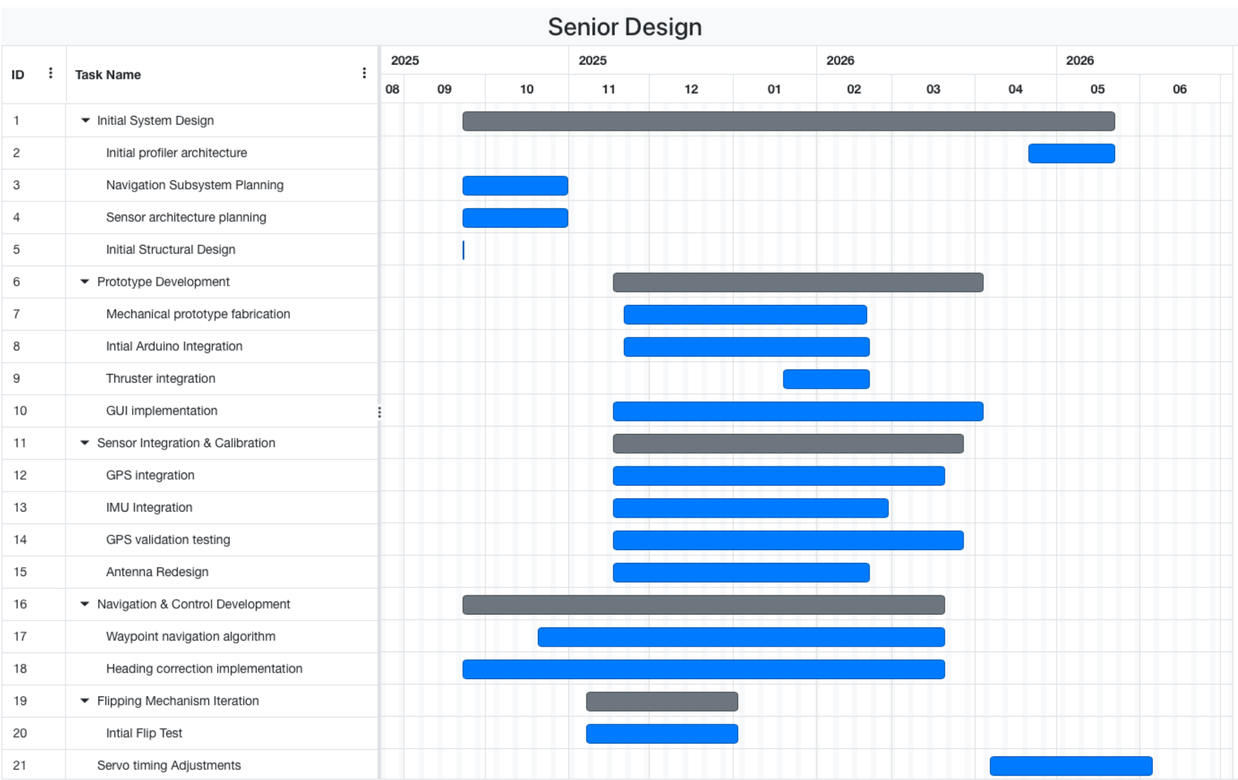

Figure 3.1: Project timeline showing subsystem development, iterative testing phases, integration milestones, and thesis preparation activities throughout the senior design project.

3.2 Budget

The MANTARAY profiler was funded through support from the Santa Clara University School of Engineering and the Robotics Systems Lab. The project budget was used to purchase the major mechanical and electrical components needed to design and build the system.

The total project spending was approximately $4,849.18, including spare parts, replacement components, and materials used during prototyping. The estimated unit cost of the final build was $2,991.08. As shown in Table 3.1, hardware components accounted for the majority of the final build cost, followed by electronic components and building materials. Hardware components totaled $2,263.97, electronic components totaled $709.13, and building materials totaled $17.98. These values are estimates because the total project spending included extra parts purchased for prototyping, replacement, and potential component failure. The Santa Clara University School of Engineering provided $2,600 in funding, and the Robotics Systems Lab provided $2,255.

Costs Breakdown	
Hardware	$2,263.97
Electronic Components	$709.13
Building Materials	$17.98
Total Cost	$2,991.08

Table 3.1: Cost breakdown by category.

Table 3.2 provides a detailed breakdown of the individual hardware, electronic, and building material costs included in the estimated final build cost.

Hardware	Costs	Electronic	Costs	Building Material	Costs
T slots	$49.92	Electronic Tray Terminal	$138	Double Sided tape	$17.98
Ball Bearings	$124.36	Arduino mega	$79.84		
Lead Screw and Flange	$462.00	Raspberry Pi	$150		
Right hand threaded flange nuts	$67.26	LED	$17		
Servos	$930	ESC	$80		
Aluminium Extrusion Holders	$19.43	IMU	$84		
Internal Rails	$44	Arduino Shield	$36.90		
O-ring flanges	$250	I2C	$90		
Clamps	$164	Connectors	$16.99		
End Cap	$67	GPS	$16.40		
Antenna tube	$16				
Antenna flange no hole	$34				
Antenna flange hole	$36				
Individual Costs	$2,263.97		$709.13		$17.98
Total					$2,991.08

Table 3.2: Detailed project budget.

A detailed Bill of Materials is provided in Appendix B. This appendix lists the major purchased components and provides a more complete breakdown of project costs.

3.3 Safety and Risk Management

Safety and risk management were an important part of the MANTARAY team's project management process because the project involves mechanical fabrication, electrical systems, batteries, moving parts, and water-based field testing. To address these concerns early, the team completed a Student Project Hazard Assessment before beginning major project work. This assessment helped the team identify project tasks, determine potential hazards, evaluate the risks associated with those hazards, and develop control measures to reduce the likelihood of injury, equipment damage, or project delays. The main hazards identified included machining, power tool use, sharp components, rotating parts such as thrusters and shafts, LiPo battery handling, electrical wiring, soldering, heavy lifting, and testing the AUV in or near water.

The team managed these risks by following a combination of training requirements, safe work procedures, engineering controls, administrative controls, and personal protective equipment. For manufacturing and assembly, only trained or certified students were allowed to operate shop equipment and power tools. Team members were required to follow Maker Lab, MECH 101L, and RSL safety procedures, including wearing safety glasses, closed-toe shoes, long pants, and tying back long hair when working near rotating machinery or tools. Before using the equipment, the team planned to inspect machines, verify guards and emergency stops, and ensure that no one worked alone during higher-risk tasks. These steps helped reduce the chance of injuries such as cuts, burns, entanglement, or impact from tools and materials.

Electrical and battery safety were also major concerns because the AUV contains microcontrollers, sensors, motors, thrusters, and LiPo batteries. To reduce electrical risks, the team planned to work on electronics only when the system was de-energized, keep components organized in a dry workspace, inspect wires and batteries before use, and use waterproof enclosures to protect electronics during testing. Leak checks were included in the testing procedure to prevent water from entering the pressure tube and damaging electrical components. LiPo batteries were handled with additional precautions because they can overheat, swell, or catch fire if damaged or improperly charged. The team planned to transport and store batteries in fire-resistant LiPo bags, inspect them before and after use, and remove damaged batteries from service.

Field testing introduced additional risks related to water safety, retrieval, and transportation of the profiler. Since the AUV may be tested from a dock, shore, tank, reservoir, or boat, the team planned for advisor or staff supervision during off-campus testing. The profiler was designed to remain positively buoyant so that it can surface if power or communication is lost, and retrieval procedures require at least two people to reduce the risk of lifting injuries or of someone falling into the water. The team also considered the risk of thruster injury by requiring visual inspections, verbal warnings before power-on, and keeping hands, hair, jewelry, and loose clothing away from moving propellers. Overall, these safety practices supported better team coordination by making responsibilities, procedures, and emergency responses clear before testing began. This allowed the team to reduce risk while maintaining steady progress on the project.

3.4 Team Allocation

Due to the multidisciplinary nature of the project, responsibilities were divided among mechanical, electrical, and software teams to ensure efficient development and testing of the autonomous profiler. Each team member was assigned ownership of specific tasks while still collaborating during subsystem integration and system-level testing. This division of labor allowed multiple aspects of the project to progress simultaneously while ensuring that each subsystem received focused attention throughout development.

The mechanical team consisted of Ysidro, Alondra, Alex, and Angelina. Alex was primarily responsible for material selection and assembly of the profiler, ensuring that components met structural requirements while remaining suitable for operation in a marine environment. Angelina focused on antenna integration, including CAD development and incorporation of the antenna system into the overall vehicle design. Alondra performed weight and center-of-mass calculations to verify vehicle stability and support the profiler's transition between horizontal and vertical orientations. Ysidro and Alondra also collaborated on the development and documentation of the integration sections of the project. In addition, Ysidro contributed to the overall CAD development and mechanical integration of new subsystems into the existing profiler platform.

The electrical subsystem was primarily developed by Gabby. Responsibilities included creating the system wiring diagram, integrating the scientific and health-monitoring sensors, and performing sensor testing and validation. This work involved integrating the Atlas Scientific dissolved oxygen, pH, temperature, and electrical conductivity sensors, as well as the leak detection system used for vehicle health monitoring. Gabby was also responsible for verifying communication between sensors and microcontrollers and troubleshooting electrical issues encountered during subsystem testing.

Ysidro additionally served as the primary systems integration lead for the project. Responsibilities included coordinating the integration of the mechanical, electrical, and software subsystems into a single operational platform. This work involved supporting hardware installation, validating communication between controllers, and conducting full-system testing to ensure compatibility between all subsystems and reliable operation of the profiler as a complete system.

The software subsystem was developed by Ashika and Divya. Ashika was responsible for the GPS navigation and mission control software, including waypoint navigation and autonomous vehicle behavior. Divya was responsible for development of the graphical user interface (GUI), which enables operators to configure missions and interact with the profiler. Together, they worked to integrate the software components and support testing of the autonomous navigation system.

While responsibilities were divided among team members, the project required continuous collaboration across all disciplines. Successful completion of the project depended on the integration of mechanical, electrical, and software subsystems into a single autonomous platform. Regular integration testing was conducted throughout development to identify compatibility issues and verify overall system functionality.

Chapter 4

Structural Design

The structural system of the M.A.N.T.A.R.A.Y. profiler serves as the physical foundation for all subsystems. It must withstand external water pressure at a depth of 30 meters, provide a rigid and modular mounting platform for all exterior components, and remain lightweight enough to be carried and deployed by a single person. This chapter covers material selection and the overall assembly of the structural system which is seen in Figure 4.1.

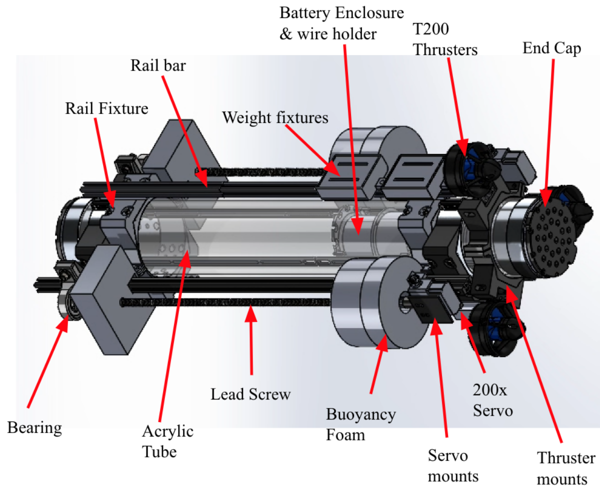

Figure 4.1: Structural Breakdown

4.1 Material Selection Pressure Housing Acrylic Tube

The primary pressure housing is a custom-ordered clear acrylic tube. Acrylic was selected for several reasons. First, it provides sufficient pressure resistance for operations at a depth of 30 meters. Second, its transparent nature allows visual inspection of internal electronics without requiring disassembly. Third, the cylindrical geometry is the most efficient shape for resisting uniform external pressure at depth, while also minimizing hydrodynamic drag during both horizontal surface transit and vertical diving. Because the tube was custom-ordered rather than sourced directly from Blue Robotics, the wall thickness was not perfectly consistent at the ends, which introduced a fitment challenge with the end caps, addressed in the assembly section below.

4.2 End Caps and Custom Aluminum Inserts

The end caps were sourced from Blue Robotics and are purpose-engineered for marine robotics applications. They are manufactured from marine-grade materials and designed to maintain a watertight O-ring seal under external water pressure. However, due to the inconsistent wall thickness of the custom tube, the end caps would not seat properly. To resolve this, CALMAX was engaged to precision machine custom aluminum inserts for both ends of the tube. Aluminum was selected for this application because it is corrosion-resistant in saltwater, strong enough to withstand the compressive forces generated by the O-ring seals at depth, and can be machined to tight tolerances to create a consistent seating surface inside the custom tube. The inserts were epoxied into both ends of the tube, and the Blue Robotics end caps were then mounted onto the inserts to ensure a reliable, repeatable seal.

4.3 Aluminum T-Slot Extrusion Rails

Four aluminum T-slot extrusion rails run the full length of the vehicle and form the structural backbone of the exterior frame. Aluminum was selected for its combination of low density, high strength, and natural corrosion resistance in saltwater environments. The T-slot channel profile was chosen specifically because it allows fixtures to be mounted and repositioned anywhere along the rails without additional drilling or fabrication. This modularity was critical for mounting the antenna, weight fixtures, and buoyancy fixture at precise positions determined during testing. Four rails were used rather than two because four-point contact provides a significantly more rigid frame that resists twisting and racking under the loads generated during flipping and diving maneuvers.

4.4 Antenna Mount and Enclosure

The antenna mount and enclosure were incorporated into the exterior structural frame to support reliable surface communication while maintaining the modularity of the profiler. The antenna enclosure is mounted vertically above the main pressure housing so that the antenna remains elevated and clear of the acrylic tube, buoyancy fixture, and other exterior components. This placement improves antenna visibility above the waterline when the vehicle is at the

Figure 4.2: Antenna Enclosure

surface and helps reduce interference from nearby structural elements.

4.5 Antenna Mount

The antenna mount was attached directly to the aluminum T-slot extrusion rails, allowing the antenna position to be adjusted during testing without requiring permanent modifications to the frame. This modular mounting approach was important because the antenna location needed to support communication performance while avoiding interference with the moving buoyancy fixture and lead screw assembly. The enclosure also provides physical protection for the antenna during handling, transport, and deployment. The antenna mount and enclosure can be seen in the following figure.

4.6 SLS Nylon PA12 Printed Components

Several structural components were fabricated using selective laser sintering with Nylon PA12 material at the SCU fabrication garage. The components produced using this method include the thruster mounts, thruster clamps, servo holder casing, servo-to-lead screw coupling, and T-slot rail fixtures. SLS Nylon PA12 was selected over FDM PLA for several important reasons. SLS parts are significantly less porous than FDM prints, which is critical for components operating in saltwater environments, where water absorption can cause swelling and mechanical degradation over time. Nylon PA12 also has inherent chemical resistance to saltwater corrosion and produces parts without layer delamination under repeated mechanical stress, which is essential for components like thruster mounts and servo attachments that experience constant cyclic loading. Additionally, the strength-to-print-time ratio of SLS made it the most practical high-performance manufacturing option available within the project timeline and budget.

4.7 Lead Screw Stainless Steel ACME TR8×8

The flipping mechanism is driven by a stainless steel ACME TR8×8 lead screw. Stainless steel was selected specifically for its corrosion resistance in saltwater environments, ensuring the screw maintains its dimensional accuracy and smooth operation over repeated actuation cycles across multiple missions. The ACME thread profile provides efficient torque transmission from the servo input and is inherently self-locking, meaning the screw holds its position with zero power draw between actuations. This self-locking characteristic is critical for a battery-powered vehicle where energy conservation is a primary design constraint.

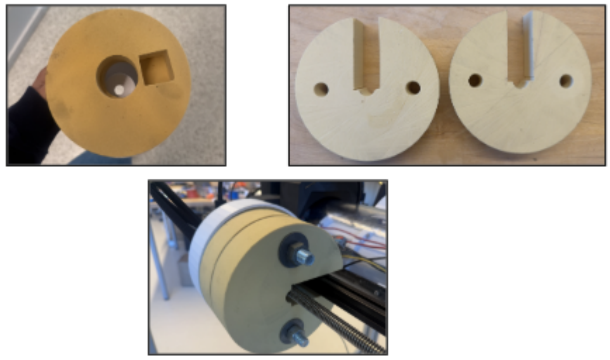

Figure 4.3: Buoyancy Foam Pieces

4.8 Buoyancy Foam and Importance

The purpose of the buoyancy foam is to ensure that once the profiler is placed in the horizontal position the profiler is almost completely at 90 degrees. Then once it is in the vertical position the profiler must be at about 180 degrees. The buoyancy foam was placed on the end with the batteries and thrusters to begin because that is where most of the mass is concentrated. The buoyancy foam is placed there because it ensures the profiler stays balanced and one side is not sinking. Once the profiler flips to the vertical position that is when the buoyancy foam is moved to the opposite end which allows the profiler to sink on the end with the batteries. Calculations were done to determine how much and where the foam will be placed in order for the profiler to flip. The buoyancy foam was cut on the lathe in order to ensure there were circular pieces that fit into the 3D insert. The buoyancy foam was cut into three pieces. This was done so that the user could change the amount of foam added depending on the deployment conditions such as fresh or salt water. This was done by running two bolts along each side of the foam and inserts and were clamped together at the end with a nut. We see an image of the buoyancy foam in Figure 4.3.

4.9 Assembly

The structural assembly of the MANTARAY profiler integrates the pressure housing, external frame, actuation system, propulsion mounts, and buoyancy system into a single cohesive structure. The design prioritizes modularity and field serviceability, with all components accessible using three or fewer common hand tools.

4.10 Pressure Housing Assembly

The acrylic tube serves as the central element of the assembly. Custom aluminum inserts were epoxied into both ends of the tube to provide consistent end cap seating surfaces. Blue Robotics end caps were then mounted onto the inserts with O-ring seals, and all penetrations through the end caps were fitted with M10 screw seals, each inspected individually to confirm the presence of the O-ring before any wet testing. A vacuum test was performed before each wet test to verify seal integrity throughout the housing.

4.11 External Frame Assembly

The four aluminum T-slot rails are mounted parallel to the acrylic tube using Blue Robotics tube clamps at each end. The T-slot rail fixtures, printed in SLS Nylon PA12, sit atop the Blue Robotics clamps and connect the rails to the tube-clamp interface. This arrangement creates a rigid four-point contact frame surrounding the tube. All exterior components, including the antenna enclosure, weight fixtures, and buoyancy fixture, are clamped directly into the T-slot channels at positions determined during testing and analysis.

4.12 Lead Screw and Actuation Assembly

The stainless steel ACME TR8×8 lead screw runs along the exterior of the acrylic tube, parallel to the T-slot rails. The screw is supported at both ends by ball bearings, which allow it to rotate smoothly under load. The Blue Trail SER-2020 servo is mounted in its SLS-printed casing and connected to the lead screw via a servo-to-lead screw coupling, also SLS-printed. The servo provides rotational torque, which the lead screw converts into linear motion, translating the buoyancy fixture along the rails to shift the center of buoyancy and induce the flip maneuver. Mechanical end stops are located at both ends of the travel range to prevent over-travel.

4.13 Propulsion Assembly

Three Blue Robotics T200 thrusters are mounted at the top of the vehicle using SLS printed thruster mounts and thruster clamps. The thrusters are arranged symmetrically in a three-point configuration. This placement ensures that when the vehicle is in its vertical diving orientation, all three thrusters point downward, counteracting its positive buoyancy and driving it to depth. The symmetric arrangement maintains vehicle stability during descent without requiring active roll correction from the control system.

4.14 Buoyancy Foam Placement

Buoyancy foam is incorporated into the assembly in two forms. Stationary foam blocks are fixed symmetrically to the exterior frame and provide baseline passive positive buoyancy, ensuring the vehicle always returns to the surface in the event of a system failure. The adjustable buoyancy fixture, which slides along the lead screw and rails, provides the movable buoyancy that shifts the center of buoyancy relative to the center of gravity to execute the flip maneuver.

Chapter 5

Flipping Mechanism

This chapter focuses on the flipping mechanism that transitions the profiler between horizontal surface travel and vertical profiling. It discusses the design requirements, trade-off analysis, physics, calculations, and final mechanism selection. The chapter explains why the buoyancy slider design was chosen and how it supports reliable orientation changes while minimizing energy use.

5.1 Requirements

To support both horizontal waypoint navigation and vertical profiling, the profiler required an orientation-changing mechanism that could operate autonomously and reliably. There are multiple ways to do this, such as moving a lever arm, adjusting buoyancy with a buoyancy bladder, or controlling thrusters. These are all feasible options; however, as a capstone team, we had a couple of constraints and requirements we wanted to abide by: simplicity and functionality.

Simplicity

Probably one of the biggest requirements we tried to follow was simplicity across four key areas: manufacturing cost, margin for error (minimizing catastrophic failure points), ease of maintenance, and the overall end-user experience. The simpler the design, the fewer critical components and custom parts are needed, which lowers the design's cost. As a senior design team working under the School of Engineering and the Robotic Systems Lab, one is limited by the resources provided. So, keeping the design simple was critical. In accordance with that, simplicity aids in eliminating single points of failure and in ensuring the profiler is built for reliability, thereby reducing complexity for mission assurance. The more moving components, the more possible failure points that will need to be studied to determine why they failed. If this is reduced, the process of troubleshooting the causes of these failures is also simplified, making the design easier to fix and understand.

Another constraint or requirement was to make the profiler easy to maintain and assemble. This idea promotes simplicity, as fewer parts to assemble mean fewer parts to maintain. This reduces the amount of material needed. While it does make relying on that part more critical, a balance was always prioritized. This ease of maintenance also helps the end user. A question that was always asked was whether someone who is not an engineer could understand, assemble, and maintain the profiler, since an engineer will not be present in the long run if something goes wrong. So, keeping things simple for the end user was key as well.

Functionality

While simplicity was a key requirement, functionality was at the heart of any decision as well. The percentage of functionality to work was always considered. The chosen flip design was based on the best balance between simplicity and functionality. One main question arose after learning that any design we chose would require flipping, since a buoyancy bladder was too complex and had too many potential failure points. It was too complex because, historically, sealing or containing water inside profilers has been an issue, as the internal electrical components and batteries are also stored inside the profiler. Ensuring everything is toleranced for sealing is challenging and requires extensive analysis. Given the available resources, time, and knowledge, it was decided to move away from this design. If moving passively vertically through the water without actively controlling buoyancy, then the profiler's orientation would need to change to dive down. The tube would need to change its orientation so that its length is parallel to the vertical position. One wants this because, if it is not done, one will experience a greater drag force. And if you are using thrusters for propulsion, you would require more energy from them, reducing the mission time and the overall number of waypoints you can hit before recharging. This is evident in some quick CFD simulations conducted on a cylindrical tube 5 inches in diameter and 3 feet long seen in Figures 5.1 and 5.2. As demonstrated, a tube experiences less hydrostatic pressure, frictional resistance, and drag when its length is aligned with the direction of the water flow. To maximize energy conservation, a profiler should not move with its largest surface area facing the flow. This highlights why a flipping mechanism is essential to optimizing energy efficiency. While we considered designing a glider capable of diving and rising in a wave-like trajectory to collect data, we ultimately chose to focus on a vertical profiler. To leverage its capabilities of diving to various depths and hovering precisely, a change in orientation is required.

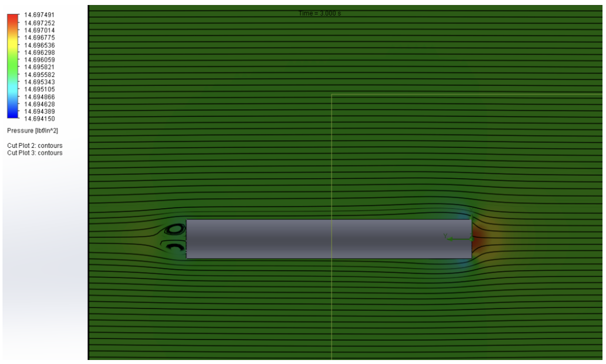

Figure 5.1: CFD simulation of the profiler body moving with its long axis aligned with the flow direction.

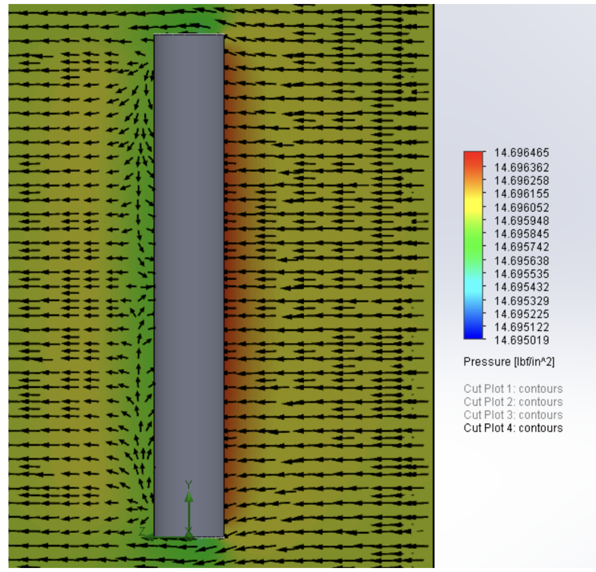

Figure 5.2: CFD simulation of the profiler body moving with its broad side facing the flow direction.

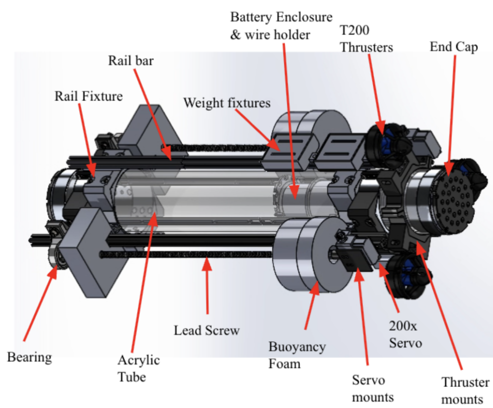

Figure 5.3: Buoyancy Slider

5.2 Trade-off Analysis

A major design decision for the MANTARAY profiler was selecting a mechanism to rotate the vehicle between horizontal travel and vertical profiling modes. The previous Waypoint Profiler project considered several vehicle-level control options, including different thruster layouts, mass shifting, buoyancy-based systems, rudders, angled thrusters, and thrust vectoring. However, MANTARAY focused more specifically on improving the flipping mechanism so that the profiler could change orientation with lower energy consumption and greater passive stability.

The MANTARAY team evaluated five main concepts: a reaction wheel, thrusters-only flipping, a buoyancy engine, a lever arm mechanism, and a buoyancy slider. These concepts were compared using design power, integration, reliability, cost, and control complexity. The goal was to choose a mechanism that could complete the flip reliably while reducing the need for continuous thruster input.

Concept	Advantages	Disadvantages	Decision
Reaction Wheel / Flywheel	Does not require external moving parts and can create rotation internally	High energy draw, vibration, bearing loads, and safety risk from a fast-spinning mass	Eliminated
Thrusters-Only Flipping	Uses existing thrusters and avoids adding a separate mechanical system	Very high energy use, requires precise IMU feedback, and may cause oscillation	Eliminated as the main approach
Buoyancy Engine	Can shift buoyancy without continuous thrust and is quiet during operation	Complex sealing, slow actuation, bulky design, and high development risk	Eliminated
Lever Arm Mechanism	Simple motion, low friction, low energy use, and initially easy to understand	Requires radial space, creates servo endpoint loads, and introduces sealing concerns	Reconsidered and eliminated
Buoyancy Slider	Low energy use, passive stability, simpler sealing, and no rotating external shaft	Requires enough foam volume and travel distance to create sufficient center-of-buoyancy shift	Selected

Table 5.1: Trade-off analysis for flipping mechanism concepts.

Table 5.1 displays the trade off analysis we performed between the different potential solutions. The initial trade study favored the lever arm mechanism because it was simple, low-cost, and energy efficient. In the scoring matrix, the lever arm received the highest weighted score of 4.65, while the buoyancy slider scored 4.15. At first, this made the lever arm appear to be the best option. However, further integration analysis revealed that the lever arm posed several practical risks not fully captured in the original scoring. These risks included sealing a rotating shaft at depth, fitting the rotating arm within the available hull geometry, and preventing repeated servo stall or endpoint loading during operation.

Because of these concerns, the team re-evaluated the buoyancy slider concept. The buoyancy slider uses lead screws driven by waterproof servos to move the syntactic foam along the profiler's body as seen in Figure 5.3. As the foam moves forward or backward, the center of buoyancy shifts relative to the fixed center of gravity. This offset creates a pitching moment that rotates the profiler without relying on continuous thruster force. This design also allows the profiler to remain more passively stable in both the horizontal and vertical orientations.

The first buoyancy slider design did not create enough center-of-buoyancy shift. The initial design used approximately 2.6 L of foam with 128.5 mm of travel but produced only about 9 mm of CB shift, which was below the 50 mm target. After redesigning the system with approximately 10 L of foam and about 500 mm of travel, the final design achieved approximately 113.7 mm of CB shift, exceeding the requirement. This showed that the buoyancy slider could meet the flipping requirement once it was properly scaled.

Ultimately, the buoyancy slider was selected because it provided the best overall balance of performance, reliability, and integration. Although the lever arm scored higher in the first trade study, the buoyancy slider became the stronger final choice after considering sealing risk, saltwater reliability, passive stability, and compatibility with the pressure hull geometry.

5.3 Calculations and Physics Breakdown

This was the selected design methodology. The core concept behind the flipping mechanism relies on manipulating the profiler's buoyancy and shifting its center of gravity using syntactic buoyancy foam, a lightweight, closed-cell material engineered to provide reliable flotation in marine environments. By intentionally creating an eccentric weight distribution, in which the overall center of mass does not align with the center of buoyancy, the offset mass acts as a moment arm. When the holding force is released, this offset generates a torque that rotates the vehicle. The following section examines this process step by step, frame by frame, starting with Figure 5.4.

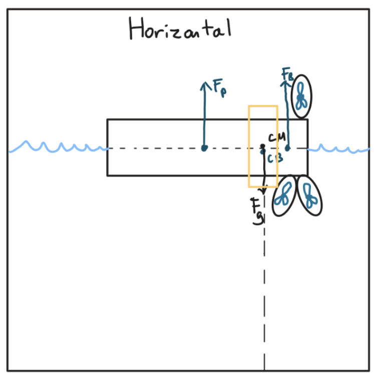

Figure 5.4: Profiler in Horizontal Position

The buoyancy foam (shown in yellow) and the buoyant force of the profiler tube collectively support the vehicle's total weight, which acts through its center of mass. In this frame, the center of buoyancy is collocated with or positioned close to the center of mass, thereby successfully counteracting the force of gravity. However, shifting the buoyancy foam away from the center of mass disrupts this balance, creating a moment arm as illustrated in Figures 5.4 and 5.5.

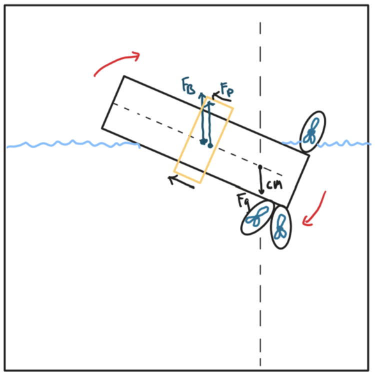

Figure 5.5: Buoyancy foam being moved away from COM

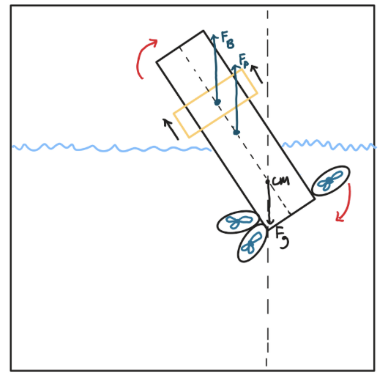

Figure 5.6: Buoyancy foam being moved away from COM

The gravitational force then rotates the profiler toward its next stable equilibrium state. At this point, as illustrated in Figure 5.6, the center of mass has swung into vertical alignment directly beneath the center of buoyancy, minimizing the distance between them.

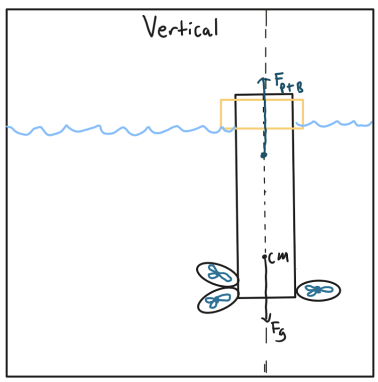

Figure 5.7: Profiler in Vertical Position

The profiler has now reached its vertical orientation, where the net torque equals zero. In this position, the system exhibits inherent static stability; if underwater currents or external disturbances displace the vehicle from its vertical axis, a restoring torque automatically returns it to the upright position. This occurs because the center of mass rests directly beneath the center of buoyancy, eliminating the moment arm through which gravity acts. A primary engineering concern is selecting an actuation system with sufficient torque to shift the buoyancy foam and transition the vehicle between its desired orientations. Preliminary background work was conducted to verify the feasibility of these load requirements.

5.4 Weight Distribution and CoM Calculations

In order to understand how much buoyancy foam will be need and how far it will need to move we had to analyze how the weight was distributed throughout the profiler. First, the mass and dimensions of each component was taken. Next, a to scale cardboard cut out of the main components, like batteries, electrical trays/ electronics, sensors, thrusters tube was arranged. The batteries are placed where the thrusters are because they are the heaviest components, hwlping the profiler to flip. This was also done so when moving vertically and horizontally, it is easier to use the thrusters' thrust in a pulling configuration instead of them pushing. The electrical trays/electronics and sensors were placed near the top of the profiler. Once the position of each component was determined the center of gravity in the x and z directions was determined. This was done in order to understand how the weight distribution impacts the position of the profiler and how to best position the components in order to ensure the profiler is balanced or its weight is favoring the dynamics that are favorable for flipping. A completed list of the Weight and Balance sheet and X center of gravity and Z center of gravity are in Appendix D.

5.5 Servo Calculations and Lead Screw Calculations

One of the constraints we had from the get-go was the type of actuation system to be used. This is because there are few actuation systems (electrical motors, hydraulic systems, or pneumatic systems) specifically designed for underwater applications. The RSL has experimented with many different motors; the ones that have performed the best are the Blue Trail 202X servo collection. The company Blue Trail uses Hitec HSR-M9382TH programmable PWM servos that they encase for use at certain underwater depths. These motors are limited to providing up to 3.3 Nm of torque. This means the loads that need to be moved must be below the 3.3 Nm threshold. Knowing this, one can find these calculations by first understanding the buoyancy torque required to maintain a net-zero torque in the horizontal position. So, if one analyzes the FBD, where F_p is the buoyancy force of the tube, F_b is the buoyancy force of the foam, and F_g is the force of gravity, in Figure 5.8, one can derive the equation 5.1.

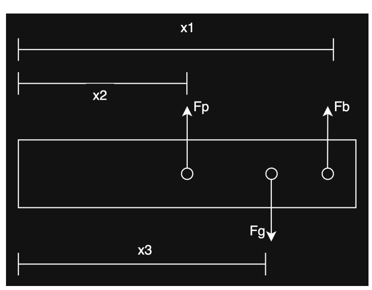

Figure 5.8: FBD in Horizontal Position

$$F_p x_1 + F_b x_2 - F_g x_3 = 0 \quad \text{(Net Torque equals zero)} \tag{5.1}$$

Because the profiler is not fully submerged while in its horizontal state, it is assumed that the net buoyant force acting on the hull and the syntactic foam is halved. Consequently, the governing equation is expressed as:

$$\frac{F_p x_1}{2} + \frac{F_b x_2}{2} - F_g x_3 = 0 \tag{5.2}$$

By isolating the buoyant force (Fb), the volume of foam required to counteract the acting moment arm can be determined. The resulting governing equation is derived as follows:

$$V_{\text{foam}} = \frac{2mx_2 - \rho_{\text{water}} V_{\text{tube}} x_1}{x_3 \rho_{\text{foam}}} \tag{5.3}$$

By positioning the foam at the longitudinal coordinate of the center of mass, the required volume ((V_{foam}))is calculated to be 91,559,024.08 mm³. This total volume can be halved because the configuration uses two servos, one on each side (the volume of the tube was found using solidworks). To determine the operational load on the actuators (F_{load}), it is critical to identify the orientation that induces peak torque. This maximum load occurs during the transition from the vertical to the horizontal position. In this state, the servos must actuate the foam, which generates a substantial upward buoyant force, against the water column. Overcoming this hydrodynamic lift is necessary to displace the foam downward, thereby minimizing the distance between the center of buoyancy (CB) and the center of gravity (CG). Given the required volume and the foam's material density, the net buoyant force can be calculated using Equation 5.4.

$$F_{\text{load}} = V_{\text{foam}} \rho g \tag{5.4}$$

Having determined the axial load, and given that a lead screw assembly will actuate the foam, standard power screw torque equations can be applied to calculate the torque required to overcome this force. To evaluate the total torque required for translation, the torque necessary to overcome thrust collar friction (T_{c}) must first be determined.

$$T_c = f_c F_{\text{load}} \left(\frac{d_c}{2} \right) \tag{5.5}$$

This collar torque is added to the torque needed to push the load (T_{push}), which is

$$T_{\text{push}} = \left(\frac{F_{\text{load}} d_p}{2} \right) \left[\frac{(f \pi d_p) + (P \cdot \cos\alpha)}{(\pi d_p \cos\alpha) - (fP)} \right] + T_c \tag{5.6}$$

The values of d_{p} is the lead screw diameter, while the α is the lead angle. The torque required to actuate the foam remains below 1Nm, provided the longitudinal offset (x2) is adjusted relative to the center of mass. If the system were configured to displace the buoyant force of the entire profiler (341.7 N · m), the required input torque would be approximately 1.6 Nm. Given the servo's maximum rating of 3.3Nm, this operating condition yields a safety factor (SF) of approximately 2.0. Consequently, it was determined that a custom gearbox design was unnecessary, as the stock actuators possess sufficient torque margins to handle the worst-case operational loads. Beyond actuator sizing, mechanical backlash was identified as a critical factor affecting positional stability. Evaluating the system's susceptibility to backlash is necessary to ensure that the foam assembly maintains its commanded position without drifting in either vertical or horizontal orientation.

$$T_{\text{lower}} = \left(\frac{F_{\text{load}} d_p}{2}\right)\left[\frac{(f\pi d_p \cdot \cos\alpha) - P}{\pi d_p \cdot \cos\alpha + fP}\right] + T_c \tag{5.7}$$

This equation helps us determine if there will be backlash. If there is, the system is self-locking; if $T_{\text{lower}} \leq 0$, there is a possibility of backlash, and the system will slip. Based on the calculations, with the current forces applied, our system is self-locking. For a closer look at the calculations, look at Appendix [x] for the Matlab script used to solve these equations and the values used. This equation determines the system's self-locking condition. If the torque required to lower the load is greater than zero ($T_{\text{lower}} > 0$), the power screw mechanism is inherently self-locking. Conversely, if ($T_{\text{lower}} \leq 0$),, the system is susceptible to backdriving and backlash, meaning the load could cause the screw to slip under external forces. Based on our analytical calculations and current operational loads, the MANTARAY's lead screw system has been verified to be completely self-locking. For a comprehensive review of the numerical calculations, input parameters, and the specific MATLAB script utilized to evaluate these equations, please refer to Appendix E.

Chapter 6

Navigation and Control

This chapter describes the navigation and control subsystem of the MANTARAY Profiler. It explains the software architecture, navigation sensors, waypoint logic, heading control, propulsion control, and graphical user interface. The chapter also discusses how the system uses GPS, IMU data, and control algorithms to support autonomous surface navigation.

6.1 Requirements

As previously mentioned, our stakeholders were interested in a system that autonomously navigates between waypoints to reduce the time and cost needed by scientists to operate the vertical profiler system. Rather than needing a boat to travel between waypoints to manually deploy the profiler, the profiler should be able to travel on the surface to pre-determined GPS waypoints. Before deploying, the operator should be able to: upload waypoint locations and target dive depths through the Graphical User Interface (GUI). Once the profiler is deployed, it should take active GPS readings to determine its current location, with the IMU collecting its current position. Then the microcontroller calculates the bearing and distance to the next waypoint and adjusts the thrusters to steer the profiler toward it. After reaching the waypoint within an acceptable error range, the system enters vertical profiling mode. This mission structure supports repeatable science missions by allowing the profiler to collect water-column data at multiple locations while reducing operator effort.

6.2 Software Architecture

In this section, we discuss the overall software architecture of the Autonomous Vertical Profiler system. The software architecture was designed to organize navigation logic, mission execution, subsystem communication, hardware control, and environmental data collection into modular components that continuously interact during autonomous operation.

The software system was developed with a strong focus on modularity, subsystem separation, and real-time feedback control. By separating major computational tasks into dedicated controllers and software modules, the architecture improves debugging, subsystem scalability, and system reliability during field deployment.

The profiler uses a dual-Arduino architecture, dividing computational responsibilities between two onboard microcontrollers. One Arduino is dedicated primarily to navigation processing and mission execution, while the second Arduino handles scientific sensor collection and low-level subsystem interaction. Separating these responsibilities reduces computational load on each controller and allows both navigation and sensor collection processes to execute simultaneously during deployment.

The Navigation Arduino acts as the primary mission controller for the profiler. This controller is responsible for mission sequencing, waypoint calculations, navigation state management, and propulsion command generation. During operation, the Navigation Arduino continuously monitors incoming navigation data and determines the appropriate control actions required to guide the profiler toward target waypoints.

The Scientific Sensor Arduino operates as the dedicated environmental sensing and data acquisition controller. This controller manages communication with scientific sensors and collects environmental measurements during profiling operations. Separating sensor acquisition from navigation processing improves overall system stability and prevents delays in navigation calculations during data collection operations.

Figure 6.1 illustrates the component-level architecture of the profiler system.

The software architecture integrates multiple major subsystems, including navigation processing, propulsion control, environmental sensing, communication systems, and subsystem monitoring. These modules communicate continuously throughout deployment in order to maintain autonomous operation and mission coordination.

The propulsion subsystem interfaces directly with the Navigation Arduino through electronic speed controllers connected to the thrusters. The navigation controller continuously generates propulsion commands to adjust translational movement and steering corrections during waypoint navigation.

The architecture also incorporates subsystem-monitoring components to track the profiler's operational health during deployment. Leak sensors, voltage monitoring systems, and onboard status indicators continuously provide feedback regarding system safety and operational status.

Wireless communication modules are integrated into the architecture to support telemetry transfer and mission moni-

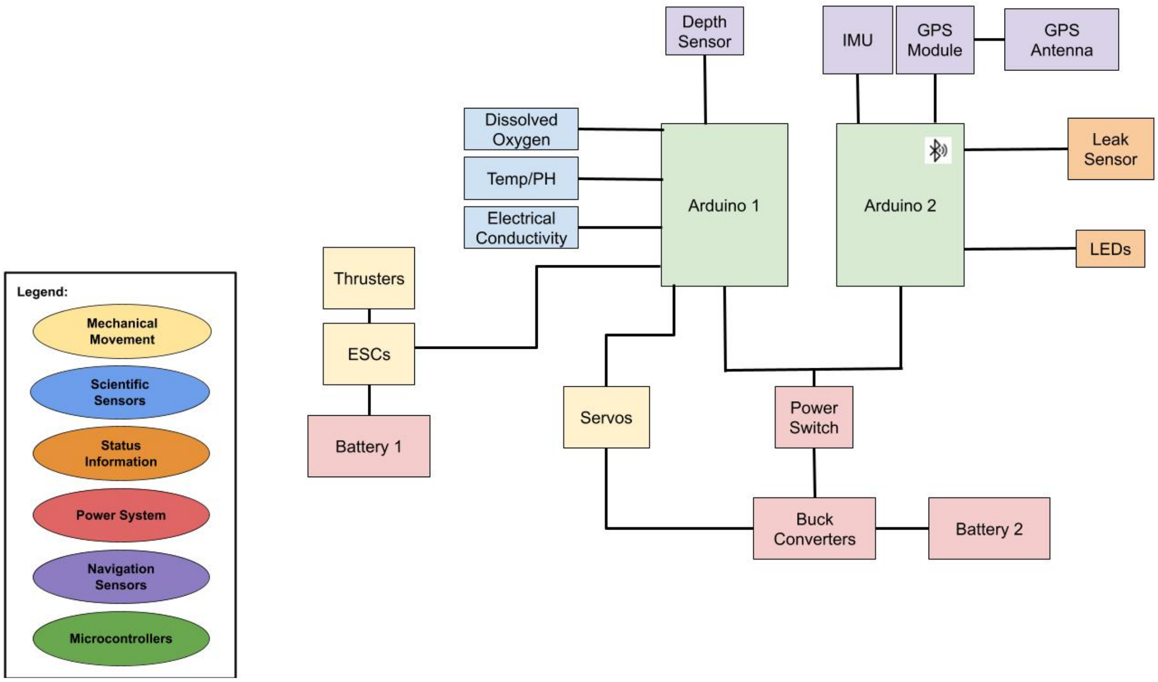

Figure 6.1: Component block diagram illustrating the integration between the navigation controller, scientific sensor controller, propulsion hardware, monitoring systems, and communication modules.

toring. Bluetooth communication is used for transferring logged JSON mission data after deployment testing.

In addition to the hardware integration architecture, the profiler software was designed around a state-machine-based operational framework to coordinate autonomous mission behavior. The state machine manages mission sequencing, operational transitions, and fail-safe behavior during deployment. Our state machine is seen in Figure 6.2.

At startup, the profiler enters the initialization and setup state, where communication with all onboard subsystems is established and verified. During this stage, the system checks sensor communication, propulsion readiness, power status, and hardware availability before allowing mission execution to begin.

Once initialization is complete, the profiler enters waypoint navigation mode if valid waypoints remain in the mission plan. During waypoint navigation, the Navigation Arduino continuously reads GPS position data and determines the profiler's current position relative to the target waypoint.

Using the current GPS coordinates and target waypoint coordinates, the navigation controller calculates the desired bearing and distance error. Simultaneously, orientation feedback from the BNO055 inertial measurement unit is used to determine the profiler's current heading. The difference between the target bearing and the measured heading yields a heading correction that guides steering behavior.

The navigation controller then generates propulsion commands, which are transmitted to the thrusters via the electronic

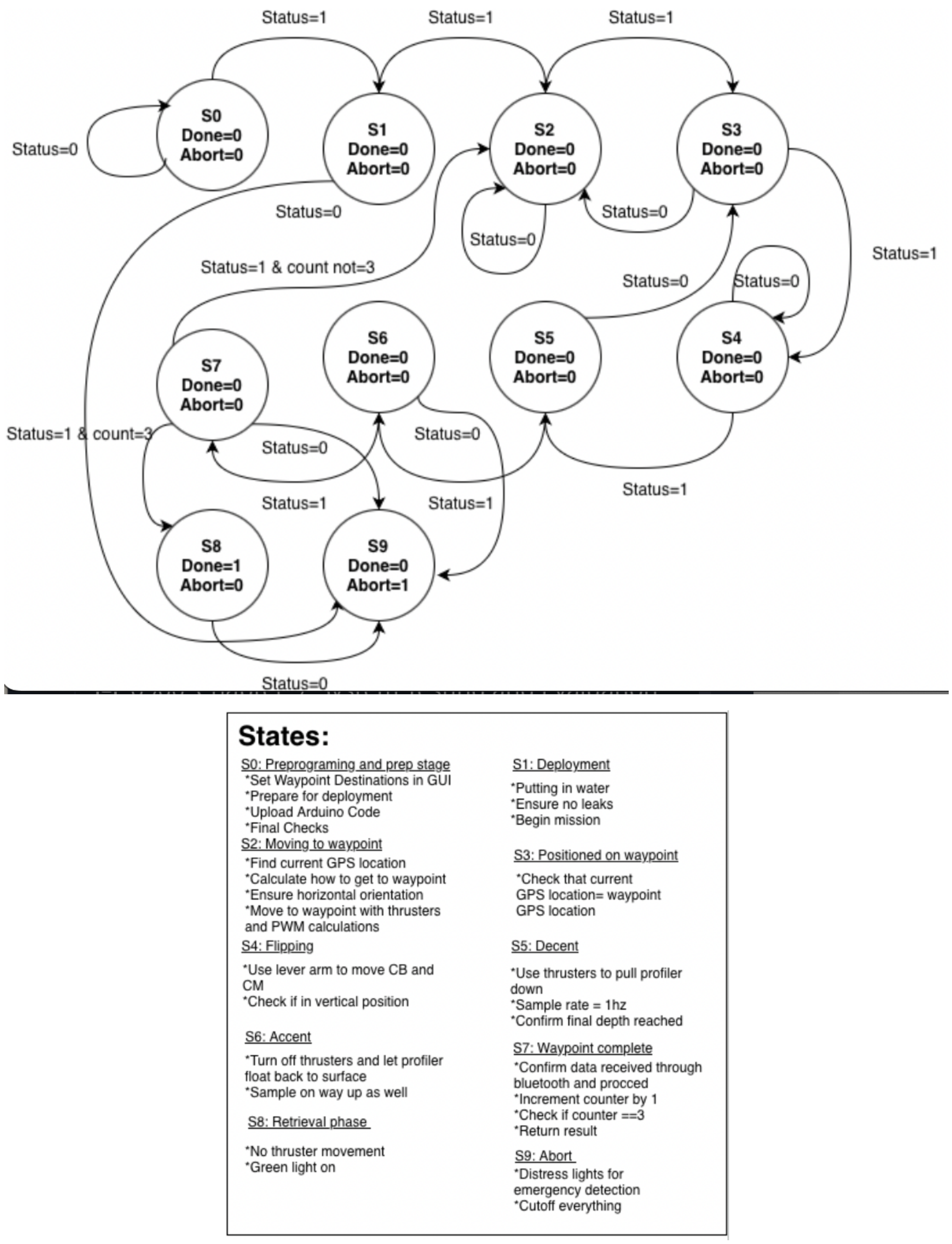

Figure 6.2: State machine diagram representing the operational behavior of the Autonomous Vertical Profiler during deployment and profiling missions.

speed controllers. This closed-loop feedback process continuously updates steering corrections and propulsion outputs until the profiler reaches the waypoint within an acceptable margin of error.

Once the profiler reaches the target waypoint, the state machine transitions into profiling mode. During this state, the profiler performs vertical profiling operations while simultaneously collecting environmental sensor data. The profiler transitions from horizontal orientation into vertical orientation using the mechanical flipping subsystem and begins underwater profiling operations.

While profiling, the Scientific Sensor Arduino continuously collects environmental measurements, including dissolved oxygen, conductivity, pH, and temperature. Simultaneously, the Navigation Arduino continues monitoring orientation, depth, and subsystem status to maintain stable operation during underwater movement.

After profiling operations are completed, the profiler resurfaces and returns to horizontal orientation. If additional waypoints remain in the mission sequence, the state machine transitions back into waypoint navigation mode. Otherwise, the profiler transitions into the return or idle state depending on mission completion conditions.

The software architecture also incorporates multiple fail-safe operational states. If abnormal conditions such as low battery voltage, leak detection, propulsion failure, or sensor malfunction are detected, the profiler immediately transitions into an emergency recovery state. During this state, the profiler surfaces and activates LED fault indicators to notify operators of the detected issue.

Figure 6.3 illustrates the overall mission software flow used during autonomous operation.

The mission software flow begins at the laptop interface, where mission parameters are transmitted to the Navigation Arduino. These parameters include waypoint coordinates, profiling depth, mission timing information, and operational settings required for deployment.

After receiving mission parameters, the Navigation Arduino processes the incoming mission configuration and begins executing mission states. During waypoint navigation and profiling operations, the Navigation Arduino continuously communicates with the Scientific Sensor Arduino to coordinate environmental data collection.

The Scientific Sensor Arduino remains idle until it receives a data collection command from the Navigation Arduino. Once commanded, the Scientific Sensor Arduino gathers measurements from the onboard environmental sensors and packages them into a sensor data packet.

The collected sensor packet is then transmitted back to the Navigation Arduino, where mission data is stored and organized for later retrieval. After deployment, the stored mission data can be transmitted to an external laptop through Bluetooth communication for post-processing and analysis.

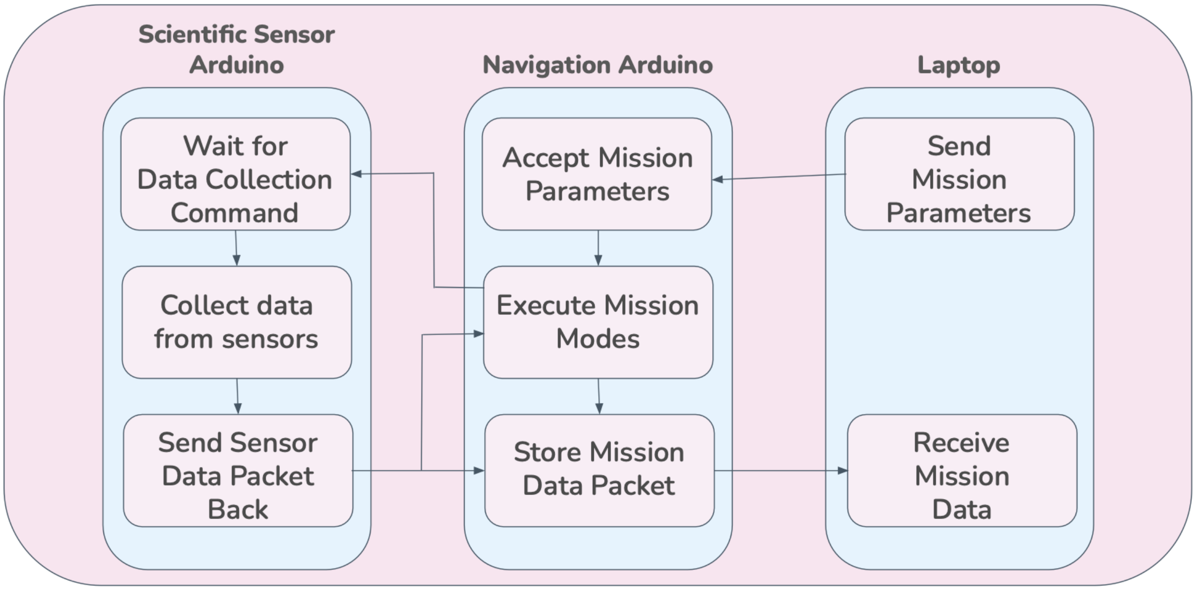

Figure 6.3: Mission software flow illustrating communication between the laptop interface, Navigation Arduino, and Scientific Sensor Arduino during autonomous mission execution.

6.2.1 Verification and Testing

Extensive subsystem verification and iterative testing were performed throughout development to validate software functionality, sensor accuracy, navigation behavior, and hardware integration prior to full deployment testing.

The verification process began with isolated subsystem testing, in which individual components were validated before complete system integration. Early testing focused on verifying GPS communication, IMU calibration, propulsion response, sensor integration, and actuator control behavior.

Calibration testing was conducted extensively to validate the accuracy of the orientation-sensing system. The BNO055 IMU was repeatedly calibrated to ensure stable heading measurements and accurate orientation feedback during navigation operations. Multiple calibration tests were conducted to minimize heading drift and improve steering accuracy during waypoint navigation.

GPS testing was also performed independently before full navigation integration. During these tests, GPS coordinate readings were validated under different environmental conditions to ensure stable positioning performance and accurate waypoint calculations.

Once individual subsystem verification was completed, the team transitioned into integrated dry testing procedures. During dry testing, the profiler was mounted on a movable cart to simulate translational motion while validating navigation algorithms, waypoint calculations, heading-correction behavior, and state transitions. These dry GPS tests allowed the team to repeatedly evaluate navigation behavior without requiring water deployment during every iteration. By using repeated cart-based testing, the team was able to rapidly debug navigation software, validate state-machine transitions, and improve steering-correction algorithms before transitioning to underwater testing.

The control system was additionally tested to verify thruster response, propulsion commands, and flipping subsystem timing behavior. Servo timing, propulsion outputs, and heading correction parameters were continuously adjusted during testing to improve movement stability and navigation accuracy.

Following dry testing, the profiler underwent multiple rounds of pool testing to validate real-world underwater behavior. Pool testing focused heavily on the reliability of the flipping mechanism, buoyancy balance, propulsion response, waterproofing performance, and orientation stability during vertical profiling transitions.

The flipping subsystem required extensive iterative testing and redesign throughout development. Multiple rounds of testing were performed to improve rotational stability and ensure reliable transitions between horizontal and vertical orientations while floating.

Subsystem communication was continuously verified throughout development to ensure reliable interaction between the Navigation Arduino, Scientific Sensor Arduino, sensors, and propulsion systems. Integration testing validated synchronization between mission execution, environmental data collection, and propulsion control during autonomous operation. The verification process also included fail-safe testing procedures. Leak-detection behavior, low-battery response, emergency surfacing procedures, and LED fault indicators were tested to confirm that the profiler could safely recover from abnormal operating conditions during deployment. The iterative verification and testing process significantly improved overall system reliability and enabled the software architecture to mature through repeated cycles of debugging, redesign, calibration, and validation before final deployment testing.

6.3 Control

The control subsystem of the Autonomous Vertical Profiler was developed to regulate autonomous navigation, propulsion control, heading correction, and underwater profiling operations throughout deployment missions. The control architecture continuously processes incoming sensor data to guide the profiler toward target waypoints while maintaining stable orientation and propulsion behavior in both surface navigation and underwater profiling states.

The profiler utilizes a closed-loop feedback control system in which real-time navigation and orientation measurements are continuously compared against desired mission parameters. Using this feedback, the navigation controller computes steering corrections and propulsion outputs required to minimize navigation error and maintain stable movement throughout operation. The control subsystem additionally manages transitions between horizontal surface navigation and vertical profiling operations during environmental data collection.

6.4 Equipment

The navigation and control subsystem integrates multiple onboard sensors and propulsion components to support waypoint navigation, orientation stabilization, underwater profiling, and autonomous mission execution. These sensors continuously provide feedback to the navigation controller during deployment, enabling the profiler to dynamically respond to changing mission conditions.

The profiler utilizes three primary navigation sensors, including a GPS module, an inertial measurement unit (IMU), and a depth sensor. Together, these sensors provide the information required for position tracking, heading correction, underwater depth regulation, and profiling operations.

The Adafruit Ultimate GPS module provides real-time latitude and longitude coordinates while the profiler operates at the surface. GPS data is continuously used to determine the profiler's current position relative to predefined waypoint coordinates during autonomous navigation missions. The navigation controller processes incoming GPS coordinates and computes both the distance and bearing error between the profiler's current location and the desired waypoint destination.

The BNO055 inertial measurement unit provides orientation and heading information for the control system. The sensor internally combines accelerometer, gyroscope, and magnetometer measurements to generate stable orientation data during operation. Heading information from the IMU is continuously compared with the desired waypoint bearing to calculate steering corrections and rotational adjustments during navigation.

The depth sensor monitors underwater depth during vertical profiling operations. This sensor allows the profiler to track vertical movement while maintaining stable underwater positioning during environmental data collection. During profiling operations, the depth sensor continuously provides depth feedback to the control system to regulate underwater motion and maintain the target profiling depth.

The propulsion subsystem consists of three thrusters connected through electronic speed controllers. These thrusters generate both translational movement and rotational steering corrections during autonomous navigation. By varying thrust output between the motors, the control system can rotate the profiler toward the desired heading while maintaining forward motion toward the target waypoint.

The navigation architecture additionally employs a dual-microcontroller architecture, with separate controllers responsible for navigation calculations and scientific sensor data collection. One controller manages waypoint calculations, navigation logic, and propulsion control, while the second controller handles scientific sensor acquisition and mission data collection. Separating these operations improves overall system responsiveness and prevents environmental sensor collection tasks from interrupting real-time navigation calculations.

Wireless communication modules were also incorporated into the system architecture to support telemetry transfer and mission data retrieval during testing. Bluetooth was primarily used to transfer logged JSON mission data files after deployment testing, while LoRa enabled long-range surface-level wireless communication during deployment operations.

LED fault indicators were integrated into the profiler to provide visual feedback to the system during emergency conditions. Different LED signals were used to indicate faults such as low-battery conditions, sensor failures, leak-detection events, and other critical system errors encountered during operation.

Throughout development, several hardware integration challenges were encountered during subsystem implementation. One major challenge was maintaining consistent IMU calibration after power interruptions and system restarts. Additional integration difficulties occurred during GPS antenna installation due to waterproofing constraints and limited cable routing space within the pressure housing.

Figure 6.4 illustrates the major navigation sensors and propulsion hardware integrated into the control subsystem.

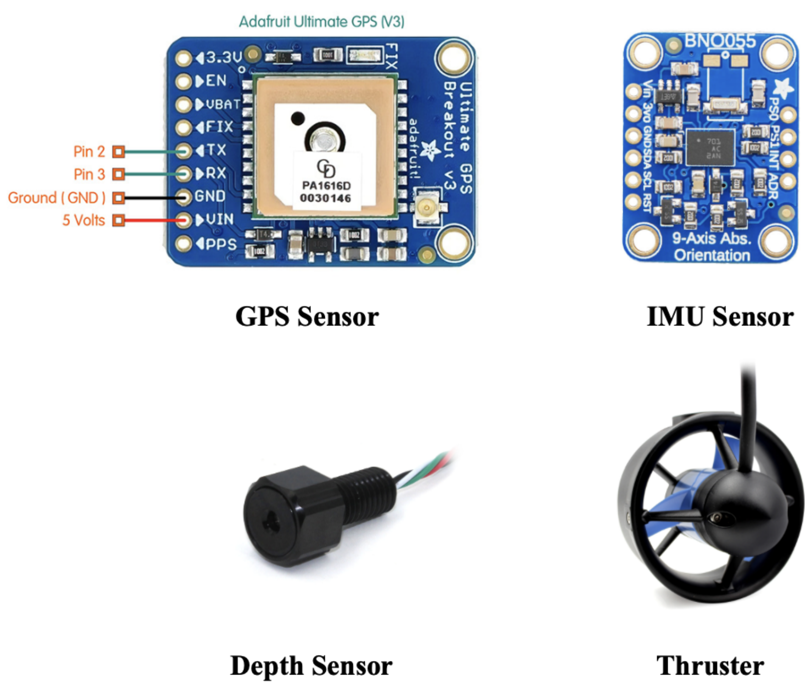

Figure 6.4: Navigation sensor integration including the GPS module, BNO055 IMU sensor, depth sensor, and propulsion thrusters used by the Autonomous Vertical Profiler. Used with permission, the GPS module image is reproduced from [2], the BNO055 IMU image from [3], the depth sensor image from [4], and the thruster image from [5].

6.5 Navigation Control System

The navigation control system continuously processes incoming GPS and orientation data to autonomously guide the profiler toward predefined waypoints during deployment missions. Figure 6.5 illustrates the overall navigation control process implemented by the profiler during autonomous operation.

The navigation process begins by loading the profiler's current GPS coordinates and the next target waypoint from the mission waypoint list. Using this information, the navigation controller computes the profiler's relative position and determines the remaining distance between the profiler and the target waypoint.

The control system then evaluates whether the waypoint has been reached within an acceptable positional margin of error. If the waypoint has not yet been reached, the navigation controller computes the desired bearing between the profiler's current GPS coordinates and the target waypoint coordinates.

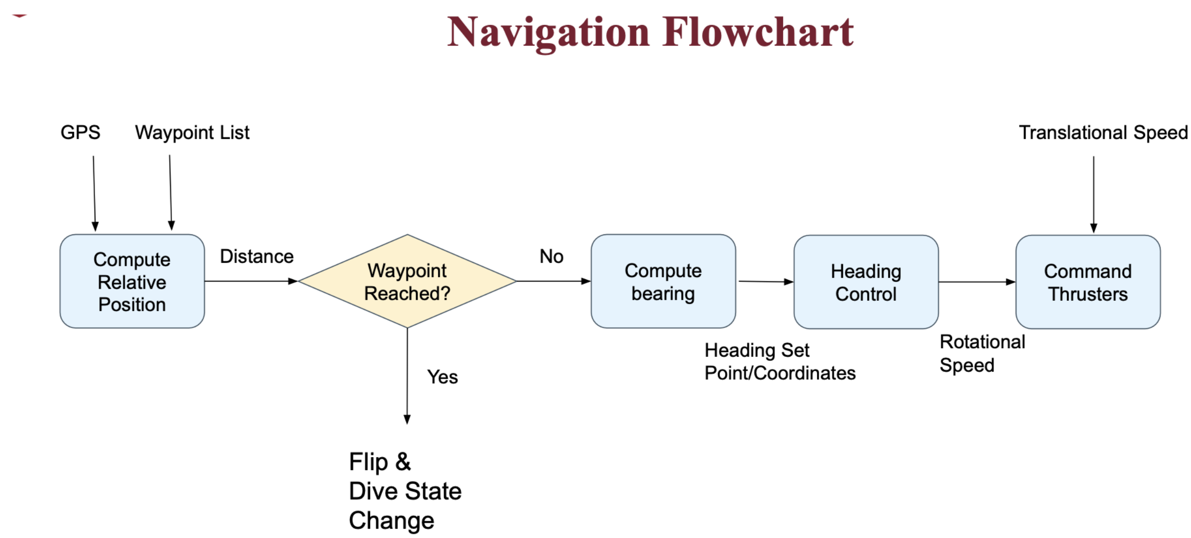

Figure 6.5: Navigation flowchart illustrating waypoint calculations, heading correction logic, and propulsion control during autonomous waypoint navigation.

After the desired bearing is calculated, the navigation controller compares the target bearing against the profiler's current heading obtained from the BNO055 orientation sensor. The difference between these two values generates a heading correction that determines the steering adjustments required to orient the profiler toward the target waypoint.

The heading correction process can be represented as:

$$Heading\ Error = Desired\ Bearing - Current\ Heading \tag{6.1}$$

Using the calculated heading error, the navigation controller computes the rotational steering corrections and propulsion outputs required to guide the profiler toward the waypoint. Translational speed inputs are also incorporated into the propulsion calculations to maintain forward movement while correcting orientation error.

The propulsion commands are then transmitted to the thrusters through the electronic speed controllers. This closed-loop feedback process repeats continuously as GPS coordinates and heading measurements are received in real time throughout navigation.

Once the profiler reaches the waypoint, the control system transitions to the flip-and-dive state, where the profiler changes orientation and begins vertical profiling operations. During this process, the profiler transitions from horizontal to vertical orientation using the mechanical flipping subsystem, while the depth sensor continuously monitors underwater depth throughout profiling operations.

The control subsystem was extensively tested during both dry and underwater deployment testing. Initial testing focused on validating individual subsystems, such as GPS communication, IMU calibration, propulsion response, and depth sensor accuracy, before full system integration.

Following individual subsystem verification, the team conducted extensive dry GPS testing using cart-based navigation experiments. During these tests, the profiler was mounted on a movable platform to simulate translational motion while validating waypoint calculations, heading-correction behavior, and propulsion-command generation without requiring full water deployment.

These dry tests allowed rapid debugging of navigation software, waypoint sequencing, and steering correction algorithms before transitioning into underwater testing procedures. Once dry testing validated overall navigation behavior, the profiler underwent multiple rounds of pool testing to verify flipping reliability, buoyancy balancing, propulsion response, waterproofing integrity, and underwater orientation stability.

The iterative testing and verification process significantly improved sensor reliability, navigation accuracy, propulsion stability, and overall system performance throughout development of the Autonomous Vertical Profiler.

6.6 Steering and Control Equations

The control equations mathematically model, simulate, and govern the system's guidance and navigation behavior. Through these governing control equations, the Global Positioning System (GPS) is integrated into a closed-loop feedback system to directly command the propulsion architecture, which, in this application, utilizes a differential-drive twin-thruster configuration. As illustrated in Figure 6.6, the control framework comprises four primary interconnected subsystems: the target bearing calculation, the Proportional-Integral (PI) error controller, the rotational (turning) dynamics, and the translational dynamics. A detailed analysis of each subsystem is found in Figure 6.6.

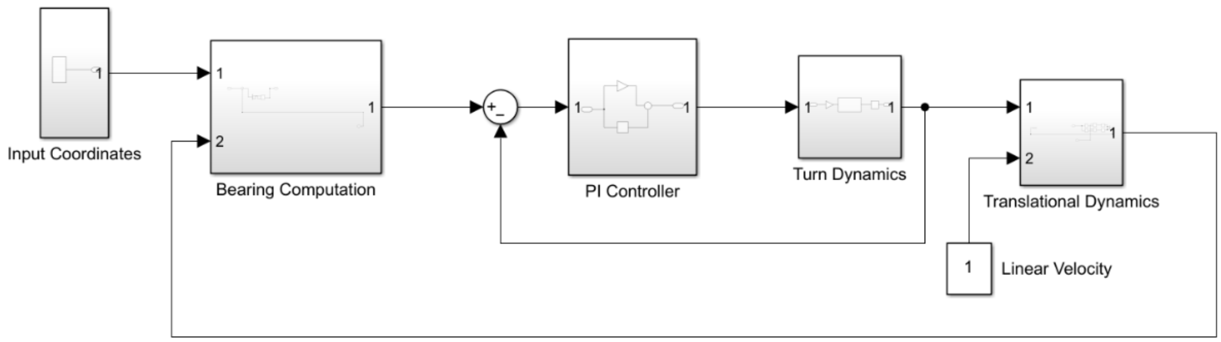

Figure 6.6: Profiler in Vertical Position

Bearing Computation

The target bearing is defined as the angle between a reference direction, typically true North, and the line of sight intersecting the vehicle's current position and its target destination. This parameter dictates the required heading command to steer the vehicle toward a specific waypoint. The guidance system accepts user-defined target coordinates $(x_{\text{target}}, y_{\text{target}})$. By comparing these to the vehicle's current GPS coordinates $(x_{\text{current}}, y_{\text{current}})$, a local right-triangle geometry is established. The relative Euclidean distances along the x and y axes are then determined by subtracting the

$$x_{\text{desired}} - x_{\text{current}} = X_{\text{distance}}$$

$$y_{\text{distance}} - x_{\text{distance}} = Y_{\text{distance}}$$

With the relative displacements Δx and Δy established, the target bearing $(\theta_{\text{desired}})$ can be computed using inverse trigonometric relationships. While standard four-quadrant trigonometry dictates that $\theta = \tan^{-1}\left(\frac{\Delta y}{\Delta x}\right)$, a two-argument arctangent function $(\text{atan2}(\Delta y, \Delta x))$ is practically implemented to resolve the full 360° heading without quadrant ambiguity. This mathematical operation yields the precise desired bearing angle for the vehicle's guidance system.

PI Error Controller

This subsystem of the control framework calculates the differential thrust commands required to minimize the heading error, the deviation between the vehicle's current heading and the desired target bearing. A Proportional-Integral (PI) architecture was selected for this application. A PI controller is highly suited for resolving heading errors because marine navigation operates within a continuous, analog domain rather than a purely discrete state space. Furthermore, PI control offers a robust, computationally efficient, and reliable solution. The derivative term (D) was intentionally omitted from the controller design because the high viscosity of the water column provides sufficient hydrodynamic damping, naturally suppressing system oscillations. High-precision positioning is outside the scope of this project; a waypoint acceptance radius of ±5 meters is considered acceptable for successful mission validation. Within this loop, the proportional term (P) provides the primary control effort, generating a correction command proportional to the magnitude of the instantaneous heading error. As the vehicle aligns with the target and the error approaches zero, the proportional contribution diminishes. To counteract steady-state errors caused by external environmental disturbances like currents, the integral term (I) accumulates residual errors over time. This continuous integration ensures that minor, persistent tracking errors are eliminated, driving the steady-state heading error to zero.

Turning Dynamics

The turning dynamics subsystem maps the commanded differential torque from the PI loop to the differential Pulse-Width Modulation (PWM) signals required by the thruster electronic speed controllers (ESCs). Mechanically, the input torque is a function of force and its corresponding moment arm. For a differential-drive vehicle, the net rotational moment is generated by the thrust differential between the port and starboard thrusters. This control torque (τ_{control}) is mathematically defined as the product of the differential thrust (ΔF) and the lateral distance (d) from the vehicle's central longitudinal axis to the centerline of the thrusters:

$$\tau_{\text{control}} = \Delta F d \tag{6.2}$$

To convert the required force into actionable PWM commands, the manufacturer's empirical thrust curves were analyzed. For computational efficiency within the controller, this non-linear curve was linearized into a first-order relationship following:

$$F = m \cdot \text{PWM} \tag{6.3}$$

where F is the net force output, m is the empirical slope constant, and PWM is the input control signal.

Furthermore, this subsystem incorporates the vehicle's plant transfer function, which dictates its physical angular response. Derived from Newtonian mechanics, the governing rotational equation of motion is expressed as:

$$\tau = J\ddot{\theta} + b\dot{\theta} \tag{6.4}$$

where J denotes the mass moment of inertia about the yaw axis (governed by the vehicle's mass distribution and geometry), b represents the hydrodynamic rotational damping coefficient (rotational resistance within the fluid), and $\dot{\theta}$ and $\ddot{\theta}$ represent the angular velocity and angular acceleration, respectively.

Integrating this rotational response yields the vehicle's current heading angle (θ). By combining this heading with the measured linear forward speed (v), the vehicle's velocity components can be mapped into the global Cartesian coordinate system using a standard kinematic transformation:

$$\dot{x} = v\cos(\theta)$$

$$\dot{y} = v\sin(\theta)$$

Integrating these global velocity components ($\dot{x}, \dot{y}$) over time yields the real-time spatial trajectory (x, y). This calculated position is continuously fed back and compared against the target waypoint coordinates to close the outer navigation loop.

The MANTARAY GUI as seen in Figure 6.7 was developed as the main operator-facing control center for the profiler. Its purpose is to make the autonomous profiler easier to plan, control, monitor, and retrieve data from during field testing. Rather than having the operator manually type raw serial commands into a terminal, the GUI provides a visual interface for configuring the mission before deployment and reviewing it afterward. This is especially important because we require that the profiler be usable by researchers, students, and field operators who may not be engineers.

Before a mission begins, the GUI allows the operator to create a mission plan by entering GPS waypoint coordinates and defining vertical profiling settings such as target depth and hold time. The waypoint planning section lets the user add, delete, and clear waypoint locations, while the route preview provides a rough representation of the planned path in the order of the entered waypoints using the relative waypoint builder.

The GUI also serves as the communication link between the operator and the onboard navigation controller. It connects to the Arduino GIGA via the browser's serial communication interface and provides buttons for common mission commands, including connecting to the Arduino, uploading waypoints, starting navigation, stopping the mission, saving and restoring calibration, listing stored waypoints, setting a heading offset, and downloading mission data. This consolidates many separate low-level commands into a single interface, making the system easier and faster to operate during testing. For out-of-water tests, the GUI parses live status messages from the Arduino and displays them in a readable format, such as GPS fix, satellite count, current latitude and longitude, current heading, target waypoint, desired bearing, heading error, distance to waypoint, current waypoint number, action state, and IMU calibration values. This live feedback helps us debug and troubleshoot the navigation features when we are out of water. For example, the operator can quickly see whether the GPS has a valid fix, whether the heading error is large, whether the profiler is moving toward the correct waypoint, or whether the IMU calibration has changed.

The interface is organized into three major screens: a planning screen, an in-progress screen, and a completion screen.

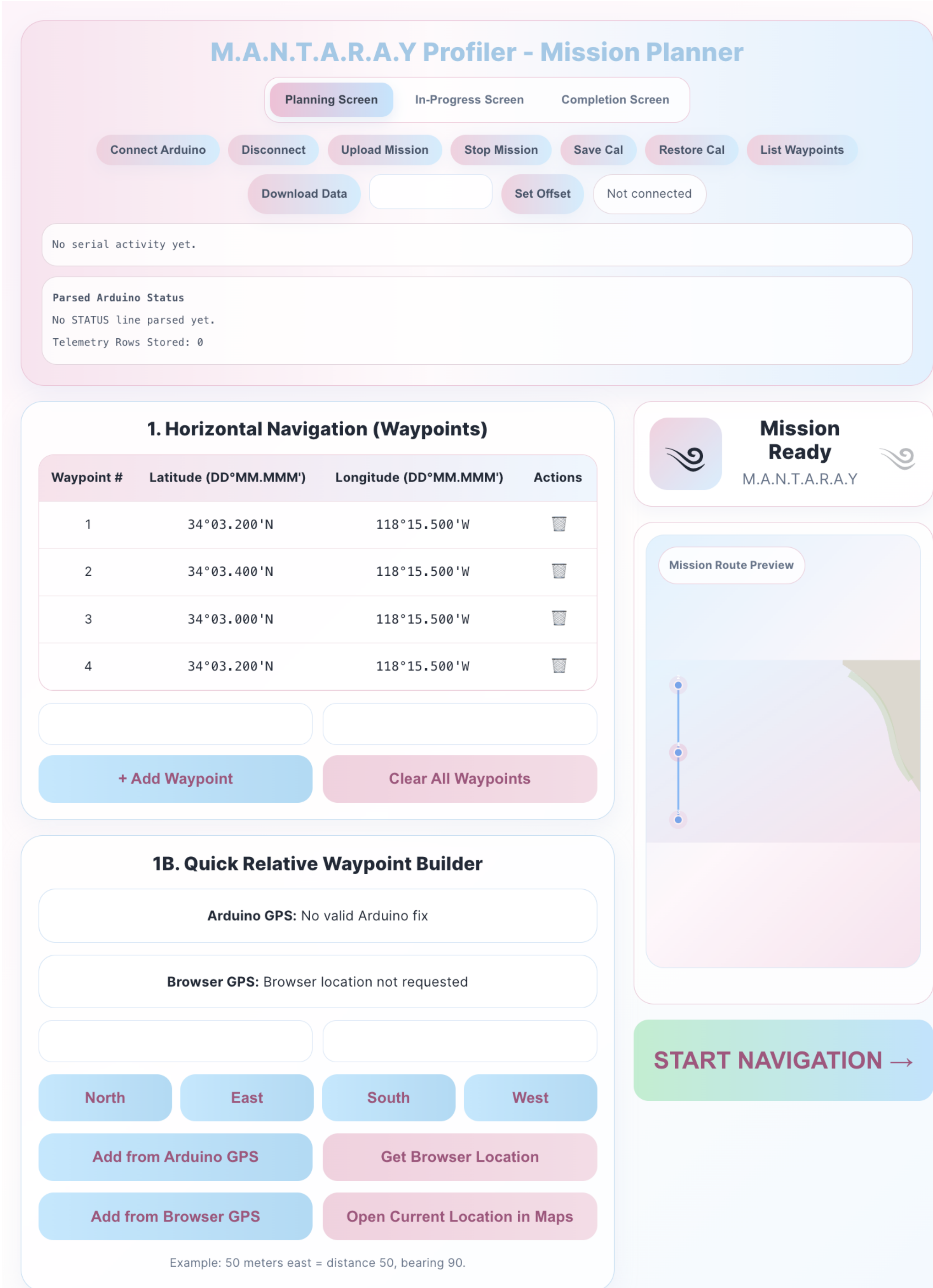

Figure 6.7: MANTARAY GUI

The planning screen is used before deployment to configure waypoints, depth steps, and mission parameters. The in-progress screen shows that the autonomous mission is active and that the system is waiting to reconnect or receive updates from the profiler. The completion screen summarizes the mission results, including planned versus achieved waypoint coordinates, depth profile information, sensor readings, and the number of telemetry rows recorded. After the mission is complete, the user can download the collected telemetry as a JSONL file for later analysis.

Overall, the GUI serves as an easy-to-use interface for operators during testing and live missions, combining mission planning, Arduino communication, live telemetry monitoring, calibration management, and data download. This makes the profiler more practical for real-world field use by reducing the technical setup required, improving visibility into the system's behavior, and enabling mission data to be collected and exported in a structured format.

Chapter 7

Scientific Sensors

This chapter describes the scientific sensor subsystem used to collect environmental and system-health data. It covers the sensor suite, wiring, communication, testing, and calibration process. The chapter explains how the profiler measures water-quality parameters such as dissolved oxygen, pH, conductivity, and temperature.

7.1 Sensor Suite

The scientific sensor suite selected for the profiler consists of Atlas Scientific sensors for dissolved oxygen, pH, temperature, and electrical conductivity [31, 29, 32, 30, 40]. These sensors were chosen because previous projects within the Robotics Systems Laboratory (RSL) demonstrated that they are reliable, accurate, and relatively simple to integrate and calibrate. Additionally, Atlas Scientific provides electrically isolated carrier boards [33], which help protect the electronics system from faults or shorts that may occur if water reaches a sensor line.

The selection of the specific sensors was determined through discussions with researchers currently using vertical profiling systems for ocean-monitoring applications. These interviews identified electrical conductivity, dissolved oxygen, pH, and temperature as the primary environmental parameters needed for evaluating water quality at different depths within the water column. The dissolved oxygen sensor is used to measure the concentration of oxygen dissolved in the water, which serves as an indicator of biological activity and ecosystem health. The pH sensor measures the acidity or alkalinity of the water, while the temperature sensor provides thermal measurements that are important for understanding water-column stratification and sensor compensation. The electrical conductivity sensor is used to estimate salinity and characterize changes in water composition throughout the depth profile. The complete scientific sensor suite used in the MANTARAY Profiler is shown in Figure 7.1. The sensor suite consists of Atlas Scientific EZO circuits paired with industrial-grade probes for dissolved oxygen, pH, temperature, and conductivity measurements.

Figure 7.1: Atlas Scientific sensor probes selected for the MANTARAY Profiler, including the industrial pH probe with temperature, industrial dissolved oxygen probe, and mini electrical conductivity probe. Source images were obtained from the Atlas Scientific website and are included for academic component-identification purposes without explicit permission [6, 7, 8].

7.2 Wiring

Figure 7.2 shows the wiring diagram for the scientific sensor subsystem. The diagram illustrates the connections between the Arduino Mega 2560, Atlas Scientific interface boards, power distribution block, and external sensor probes used throughout the system. The pH and temperature probes were implemented as a combined sensor package, reducing the number of separate probes required and simplifying integration inside the enclosure. To optimize the limited internal space available within the profiler, a power distribution block was used to distribute the Arduino Mega's 5V and ground connections to all sensor interface boards. This simplified the wiring layout and reduced the number of individual power connections required throughout the system.

A major wiring and integration consideration for the scientific sensor subsystem was reducing the potential impact of electrical noise on sensor measurements. The profiler utilizes high-current thrusters and electronic speed controllers, which are commonly associated with electrical noise that may affect sensitive sensor electronics. To reduce this risk, the scientific sensing subsystem was separated from the propulsion power system whenever possible. While electrical noise was not quantitatively measured during testing, the system architecture was designed to minimize potential interference between the propulsion and sensing subsystems.

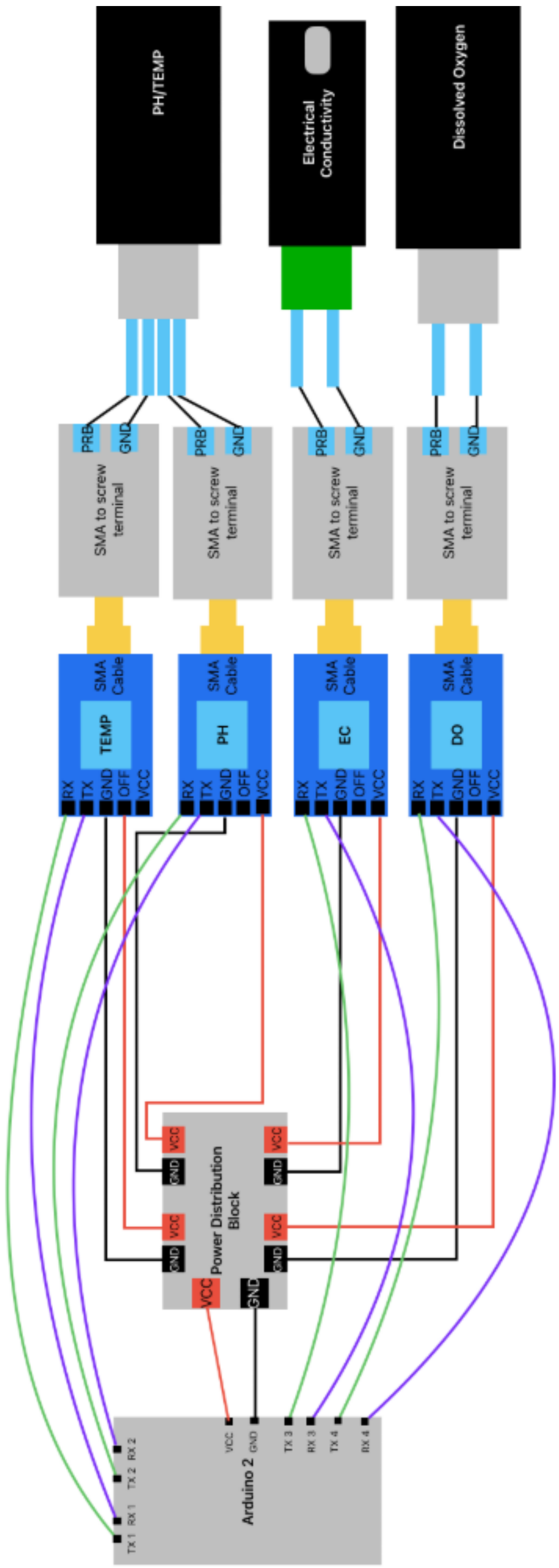

Figure 7.2: Scientific sensor subsystem wiring diagram

Each Atlas Scientific sensor communicates using UART serial communication and therefore requires both transmit (TX) and receive (RX) connections to the Arduino Mega 2560 [31, 29, 32, 30, 35]. The TX and RX lines from each sensor were crossed to the corresponding RX and TX pins on the microcontroller to establish bidirectional communication.

Each sensor probe connects to its electrically isolated carrier board before interfacing with the microcontroller [33]. These isolation boards help reduce the possibility of electrical interference and provide protection between the probes and the rest of the electronics system. SMA and BNC bulkhead connectors were additionally used to create waterproof and removable external probe connections while maintaining enclosure integrity.

The Arduino Mega 2560 was selected for the scientific sensing subsystem because it provides multiple hardware serial ports, allowing several sensors to operate simultaneously [35]. Due to the number of serial interfaces required by the Atlas Scientific sensors, the Arduino Mega was dedicated primarily to sensor communication and data collection while other vehicle functions were handled independently. This architecture simplified integration and reduced communication conflicts between subsystems.

7.3 Testing

7.3.1 Individual Sensors

Each scientific sensor was initially tested individually before full system integration. During these tests, every sensor was connected independently to the Arduino Mega to verify communication, power delivery, and sensor readings. Test code was written to request readings from each sensor and print the returned values to the serial monitor.

The dissolved oxygen, pH, temperature, and electrical conductivity sensors were all verified to return measurements and respond to communication requests under normal operating conditions. Calibration commands provided by Atlas Scientific were also tested during this stage to ensure that communication between the microcontroller and sensor circuits was functioning properly. These individual tests were important because they allowed sensor-specific issues, such as incorrect wiring, unstable connections, or configuration errors, to be identified and resolved before integrating all sensors into a single system.

7.3.2 Integrated Sensors

After standalone testing, the sensors were integrated into one subsystem connected to the Arduino Mega. The integrated testing phase focused on verifying that all sensors could operate simultaneously while reliably gathering data.

A combined software architecture was developed to sequentially request and collect measurements from each sensor. Sensor readings were formatted and transmitted to the serial monitor for verification. An example of the combined sensor output generated during integrated testing is shown in Figure 7.3. The successful acquisition of dissolved oxygen, pH, temperature, conductivity, and leak sensor data demonstrated proper communication between the Arduino Mega and each sensor subsystem.

The scientific sensor subsystem was also required to collect measurements at a rate suitable for the profiler's motion through the water column. Because the profiler measures environmental conditions while moving vertically, the sampling rate must be fast enough to capture changes in water quality with depth without producing unnecessary or redundant data. The initial measurement rate was set to one sample per second, or 1 Hz. This rate provides a reasonable starting point for collecting depth-dependent measurements during profiler operation while limiting the amount of data produced during each mission.

Integrated testing showed that the sensor subsystem could collect and report measurements at the initial 1 Hz sampling rate. Therefore, the scientific sensor subsystem meets the initial measurement-rate requirement for the current stage of development. During future field testing, this sampling rate should be adjusted based on the actual profiler speed, the depth resolution needed by researchers, and the accuracy of the collected data at different travel speeds. If field data shows that important changes in water quality occur over shorter depth intervals, the sampling rate may be increased. If the data shows that measurements remain stable over longer intervals, the sampling rate may be reduced to simplify data storage and processing.

One of the primary challenges during integration was combining all sensor communication code into a single program. Since each Atlas Scientific sensor requires dedicated TX and RX serial communication lines, the number of available hardware serial ports became a limitation when attempting to interface both navigational and scientific sensors through a single microcontroller. To address this issue, the system architecture was divided between two Arduinos. The Arduino Mega 2560 was dedicated to handling the scientific sensor subsystem because it provided enough serial ports for sensor communication, while the Arduino GIGA R1 WiFi handled navigation, control, and communication independently [36]. Separating the responsibilities simplified the software integration process, reduced communication conflicts, and improved organization.

Integrated testing confirmed that all sensors could successfully operate together while continuously transmitting environmental data throughout simulated mission operation. The incremental testing approach of validating individual sensors before subsystem integration proved valuable in identifying and resolving hardware and software issues throughout development.

```
Requesting sensor readings...

--------- SENSOR READINGS ---------
Temperature: 24.25 C
pH: 6.54
Dissolved Oxygen: 2.61
Conductivity: 192.60 uS/cm
Leak Sensor: WATER DETECTED
-------------------------
```

Figure 7.3: Example serial monitor output showing integrated scientific sensor data

7.4 Calibration

Calibration procedures were researched and partially implemented during development to ensure accurate environmental measurements from each sensor before deployment. Atlas Scientific provides calibration procedures specific to each sensor type, which can be executed through software commands sent from the Arduino Mega [31, 29, 32, 30].

The pH sensor calibration process uses standard buffer solutions with known pH values, while the conductivity sensor is calibrated using conductivity reference solutions. The dissolved oxygen sensor calibration procedure involves atmospheric and solution-based calibration methods recommended by the manufacturer. Temperature measurements can additionally be verified against a reference thermometer to confirm reasonable accuracy.

Although full physical calibration of all sensors was not completed during the project timeline, the communication architecture and software commands required for calibration were implemented and software verified. Previous RSL teams working with Atlas Scientific sensors have demonstrated successful calibration and deployment using similar procedures. Therefore, the system architecture developed in this project supports future calibration and deployment efforts without requiring major hardware or software redesign.

Chapter 8

Power

This chapter explains the power subsystem of the MANTARAY Profiler. It describes the power distribution architecture, battery configuration, voltage regulation, and estimated power consumption. The chapter also explains how the power system supports the thrusters, microcontrollers, sensors, servos, and other onboard electronics during operation.

8.1 Power Diagram

The profiler utilizes a dual-battery power architecture to separate the high-current propulsion system from the sensitive electronics and actuation systems. The power distribution system was divided into two diagrams for clarity. Figure 8.1 shows the thruster power distribution system, while Figure 8.2 shows the regulated electronics power distribution system.

The propulsion subsystem is powered independently using a 14.8V lithium-ion battery connected directly to the three electronic speed controllers (ESCs) [38]. Each ESC receives pulse-width modulation (PWM) control signals from the navigation Arduino and regulates the power delivered to each Blue Robotics T200 thruster [37, 19]. Blue Robotics components were selected because they are commonly used throughout the Robotics Systems Laboratory (RSL) and have previously demonstrated reliable underwater performance in marine robotics applications. The T200 thrusters and BESC30 speed controllers are widely used in small autonomous underwater vehicle platforms due to their reliability and underwater operating capability [19, 37]. Since the thrusters are designed to operate directly from the battery voltage, no voltage conversion was required for the propulsion subsystem. Separating the thruster power system from the electronics reduced electrical noise and prevented large current draws from interfering with sensor and microcontroller operation.

A second 14.8V lithium-ion battery [38] powers the electronics and actuation subsystem. This battery powers two

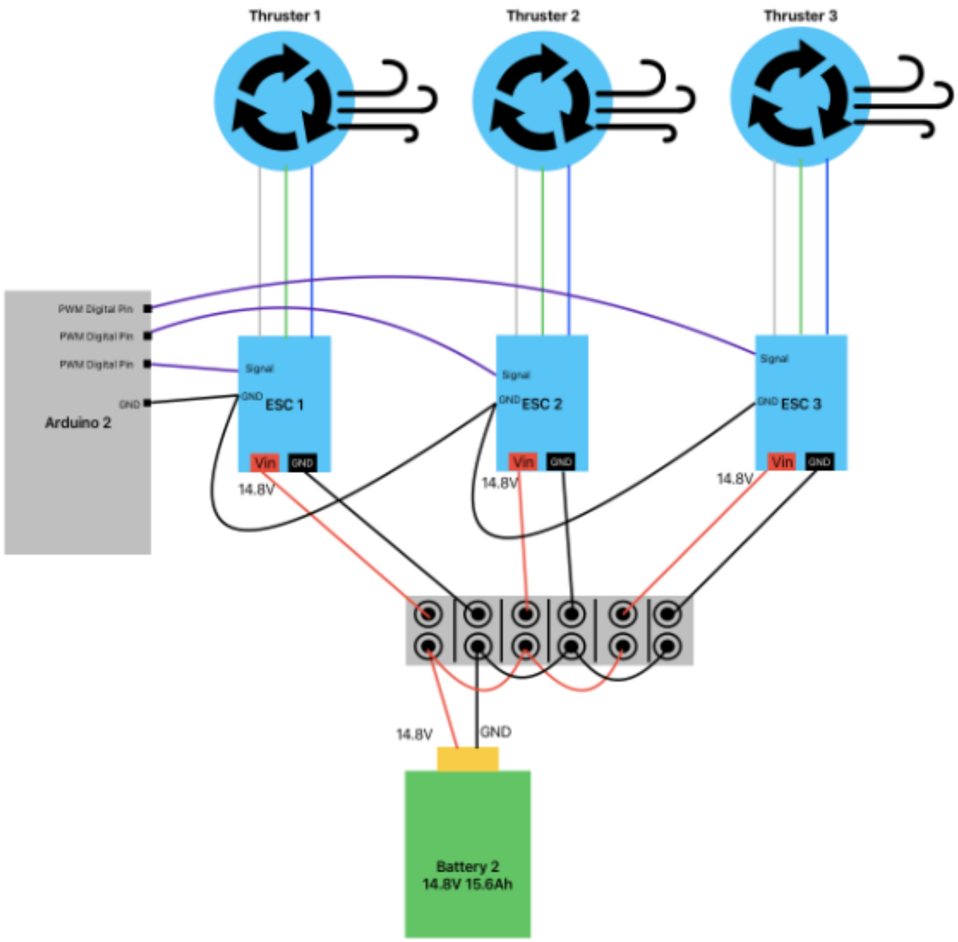

Figure 8.1: Thruster power distribution wiring diagram.

buck converters, which step the voltage down to the levels required by the onboard electronics. The converters used in the profiler have two outputs: one output at the original input voltage and a second adjustable output between 3.3V and 14.8V. One buck converter is set to output 5V for the Arduino Mega 2560 and Arduino GIGA R1 WiFi microcontrollers [35, 36], while the second buck converter outputs 7V for the servo motors that actuate the buoyancy-shifting mechanism.

The servo motors receive PWM control signals from the Arduino and use the regulated 7V supply for actuation [39]. A centralized terminal distribution block was used to simplify wiring and distribute regulated power to the servos. An external power switch was additionally included between the battery and electronics subsystem to allow the profiler to be safely powered on and off during testing and deployment. This dual-battery configuration improved system reliability by isolating high-current propulsion loads from sensitive scientific and navigation electronics while also simplifying subsystem power management.

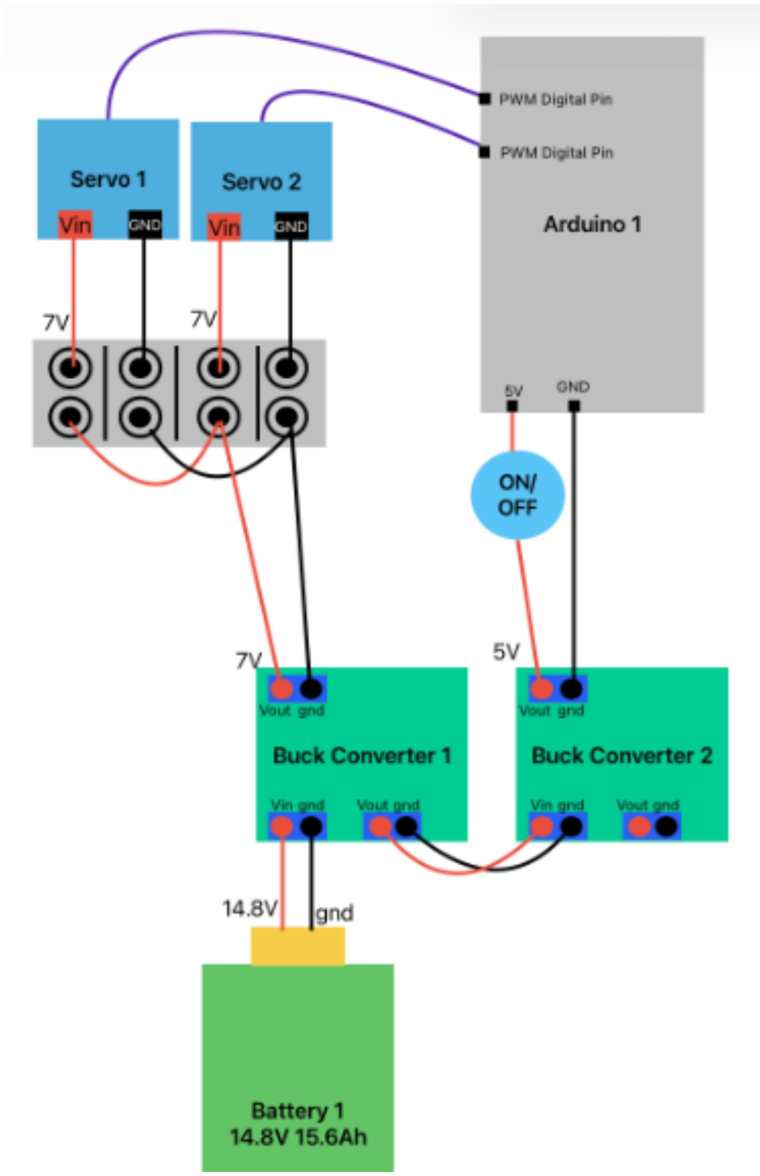

Figure 8.2: Arduino and electronics power distribution wiring diagram.

8.2 Power Calculations

Power calculations were performed to estimate the profiler's expected mission runtime and verify that the selected batteries could support all required mission operations with an additional safety margin. The results can be seen in Figure 8.3.

Both battery systems use 14.8V lithium-ion batteries rated at 15.6Ah [38], corresponding to approximately 230.88Wh of stored energy. The propulsion battery was sized based on the expected current draw of the three Blue Robotics

Battery 1	Values
Battery Voltage (V)	14.80
Battery Capacity (Ah)	15.60
Battery Energy (Wh)	230.88
Number of thrusters	3.00
Max Current per thruster (A)	22.00
Max current all thrusters (A)	66.00
Thruster on time per waypoint (s)	220.00
Number of waypoints	3.00
25% Saftey margin	1.25
Average current all thrusters (A)	33.00
Energy per waypoint (Wh)	29.85
Energy per three waypoints (Wh)	89.54
Energy per three waypoints with 25% margin (Wh)	111.93
Remaining battery energy (Wh)	118.96
Percent of remaining battery energy (%)	48.48

Battery 2	Values
Battery Voltage (V)	14.80
Battery Capacity (Ah)	15.60
Battery Energy (Wh)	230.88
Servos (2×) Energy (Wh)	9.99
Arduinos (2×) Energy (Wh)	0.06
Science Sensors Energy (Wh)	0.23
Total Energy for three waypoints (Wh) (with 25% margin)	10.28
Remaining battery energy (Wh)	220.60
Remaining Capacity (%)	95.55

Figure 8.3: Power calculation summary

T200 thrusters, which represent the system's largest power draw.

Each thruster has a maximum current draw of approximately 22A [19], resulting in a theoretical maximum combined current draw of 66A for all three thrusters operating simultaneously. Since the profiler is not expected to continuously operate at full thrust, an average operating load of approximately 50 percent throttle was assumed during mission calculations. This reduced the estimated average propulsion current draw to approximately 33A.

Mission planning assumed three waypoint traversals with an estimated thruster operation time of approximately 220 seconds per waypoint. Using these assumptions, the propulsion subsystem consumed approximately 29.85 Wh per waypoint and 89.54 Wh for all three waypoints combined. A 25 percent safety margin was then applied to account for environmental uncertainties and operational inefficiencies, increasing the estimated propulsion energy requirement to 111.93Wh.

After applying the safety margin, approximately 118.96 Wh of battery capacity remained available, corresponding to roughly 48.48 percent of the battery energy remaining after mission completion. These calculations demonstrated that the propulsion battery capacity was sufficient to support the planned mission profile while maintaining a significant energy reserve.

Separate calculations were performed for the electronics subsystem. The servos, Arduinos, and scientific sensors were found to consume substantially less energy compared to the propulsion system. Combined electronics power consumption for the full mission, including a 25 percent safety margin, was estimated at approximately 10.28 Wh. This resulted in approximately 95.55 percent remaining capacity in the electronics battery after mission completion.

Overall, the power calculations demonstrated that the selected battery configuration could reliably support autonomous waypoint navigation, buoyancy actuation, scientific sensing, and data collection for the planned mission duration while maintaining adequate operational safety margins.

Chapter 9

System Testing and Evaluations

This chapter presents the system testing and evaluation performed on the MANTARAY Profiler. It summarizes the tests used to evaluate the flipping mechanism, navigation behavior, subsystem integration, and overall system functionality. The chapter also discusses testing limitations and identifies areas for future validation.

9.1 Flipping

To evaluate the feasibility of the flipping mechanism, preliminary center-of-gravity (CG) and weight distribution testing were conducted. These initial physical trials employed a scaled cylindrical hull alongside early-stage functional prototypes, as documented in Figures 9.1, 9.2, 9.3, and 9.4.

These initial physical models provided critical empirical data regarding the exact ballast weight and foam volume required to achieve the target pitch configurations. Following months of system assembly and the mitigation of integration challenges during the transition from the CAD model to the physical architecture, a final functional prototype was completed for experimental validation. As documented in Figures 9.5, 9.6, and 9.7, preliminary pool testing was conducted in a controlled residential setting. The testing protocol evaluated transient actuation: the servos were commanded to translate the foam forward (counterclockwise actuator rotation) for 175 seconds, pause for a 10-second dwell, then reverse direction (clockwise actuator rotation) for 175 seconds to return to the baseline configuration. Upon executing this script, the vehicle successfully demonstrated the intended hydrodynamic behavior. The profiler initiated the sequence in a stable horizontal state and smoothly pitched downward toward a vertical orientation as the foam displaced.

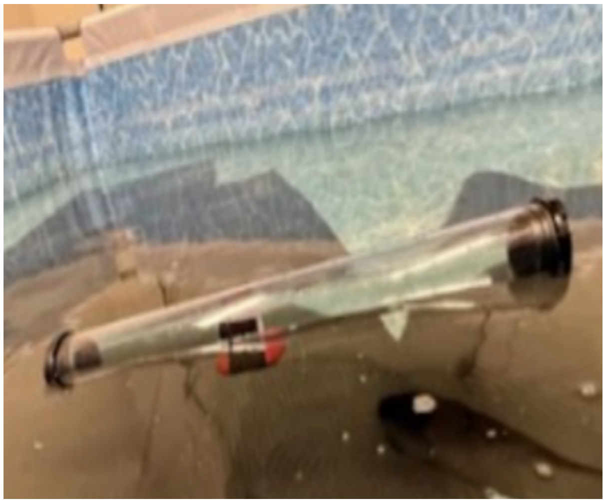

Figure 9.1: Profiler Model 1

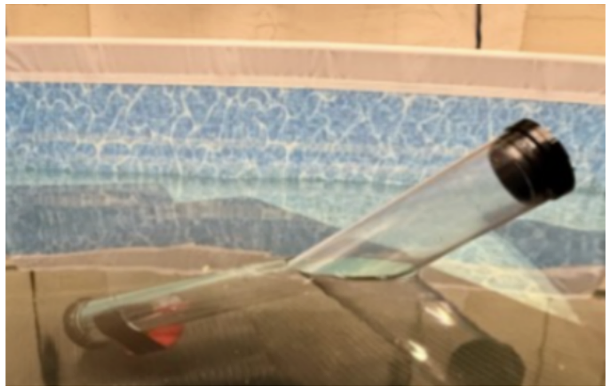

Figure 9.2: Profiler Model 2

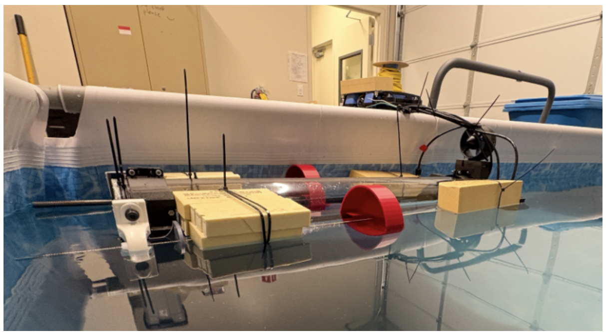

Figure 9.3: Profiler Model 3

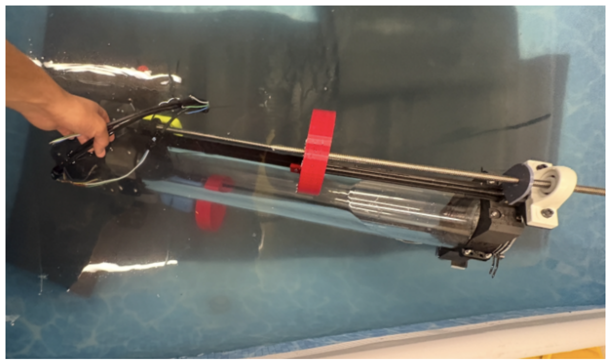

Figure 9.4: Profiler Model 4

Because of the shallow depth of the testing pool, the vehicle's nose contacted the floor during this transition, preventing full validation of the vertical steady-state phase. Nevertheless, following the 10-second programmed delay, the actuators successfully reversed the foam's displacement. This structural shift generated the necessary restorative moment, returning the profiler to its baseline horizontal orientation. These results establish a fundamental proof of concept for the mechanical design. To fully characterize the vehicle's dynamic stability and complete flipping envelope, subsequent field trials must be conducted in a deeper aquatic environment.

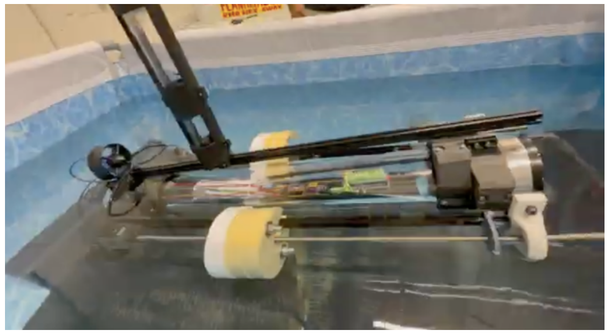
Figure 9.5: Profiler in Horizontal Position 1

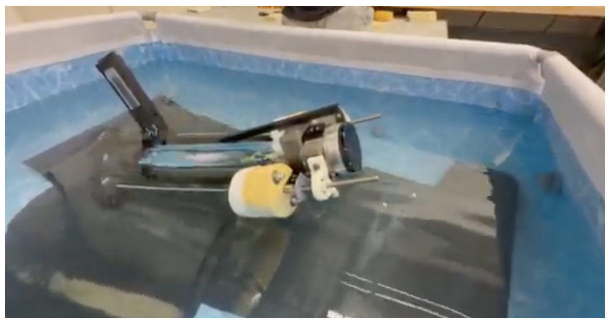
Figure 9.6: Profiler in Horizontal Position 2

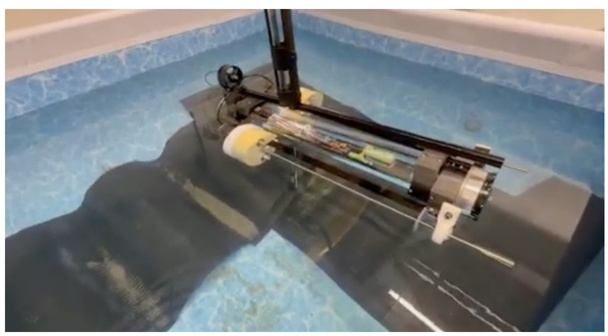
Figure 9.7: Profiler in Horizontal Position 3

9.2 Navigation

While we were unable to test navigation in deployment, we conducted several dry tests. These tests were designed to verify that the system could correctly get GPS data, calculate the bearing and distance to a target waypoint, correct its heading during motion, and determine when the target waypoint had been reached.

While testing, we used a predetermined GPS waypoint on land and placed the MANTARAY profiler on a cart. We used our GUI system's test mode to have it output live directions on where to push the cart. While running the test, the system logged telemetry data including latitude, longitude, waypoint index, desired bearing, current heading, heading error, distance to waypoint, GPS fix status, satellite count, and navigation state. We used these pieces of data to log the MANTARAY's path and determine whether the navigation was working properly.

Across the dry tests, the system consistently demonstrated the expected navigation behavior. As the MANTARAY moved closer, the reported distance to the active waypoint decreased, indicating that the system was progressing toward the target. The heading error also changed over time as the system corrected its orientation toward the desired bearing. In the Mission 2 test, for example, the system began approximately 111.24 meters from the waypoint and reached a final distance of approximately 1.18 meters, at which point the navigation state changed to arrived. This confirmed that the arrival detection logic was functioning correctly during the dry-run evaluation.

Overall, the dry testing demonstrated that the autonomous navigation subsystem functioned correctly under controlled test conditions. The system was able to process GPS data, move toward target waypoints, reduce heading error, and identify arrival at the waypoint. While full deployment validation remains future work, the dry-run results support the conclusion that the navigation subsystem met its core functional objectives.

Chapter 10

Professional Issues and Constraints

This chapter discusses the professional issues and constraints associated with the MANTARAY Profiler. It considers ethical responsibilities, societal impact, civil engagement, environmental impact, and economic considerations. These topics are important because the system is intended to operate in natural water environments and support environmental data collection.

10.1 Ethical Considerations

MANTARAY Profiler raises several ethical considerations because it is designed to operate autonomously in marine environments while collecting environmental data. As engineers, our first responsibility is to protect public safety, marine ecosystems, and the reliability of the data being collected. Since the profiler is intended to support ocean health monitoring, the system should be operated in a way that does not harm marine life, disturb sensitive habitats, or introduce unnecessary pollution into the water.

One major ethical responsibility is ensuring that the data collected by the profiler is accurate and useful. The system measures important water-quality parameters such as dissolved oxygen, pH, temperature, conductivity, and depth. If these readings are inaccurate due to poor calibration or sensor failure, researchers could draw incorrect conclusions about the health of a body of water. For this reason, sensor calibration, maintenance, and clear documentation are ethical concerns as much as technical concerns.

Another ethical consideration is safety during autonomous operation. Because the profiler navigates between waypoints and performs vertical dives, it must be designed to reduce the risk of failure, loss, or unsafe behavior in the water. The inclusion of leak detection, voltage monitoring, LED indicators, and fail-safe surfacing enhances the design's ethical responsibility by helping prevent damage to the system and reducing the risk of environmental harm.

Finally, the project should be designed with accessibility in mind. Ocean-monitoring technology can be expensive and limited to well-funded institutions. The MANTARAY Profiler aims to make water-column data collection more affordable and practical for universities, smaller research groups, and coastal communities. This supports a more equitable approach to marine research by making environmental data collection more available to groups that may not have access to large research vessels or commercial AUV systems.

10.2 Science, Technology, and Society

The MANTARAY Profiler connects science, technology, and society through autonomous engineering systems that support environmental research. Scientifically, the profiler helps collect water-quality data to better understand marine and freshwater environments. Measurements such as dissolved oxygen, pH, conductivity, temperature, and depth are important because they provide insight into ecosystem health, water chemistry, and changes throughout the water column.

From a technology standpoint, the profiler integrates mechanical design, electrical systems, embedded controls, sensors, communication, and software into a single platform. The system uses autonomous waypoint navigation to traverse the water surface, then transitions to vertical profiling mode to collect data at depth. This approach reduces the need for constant human control and allows data to be collected more efficiently than manual methods.

The societal impact of this technology is significant because better ocean data can support better environmental decision-making. Coastal communities depend on healthy marine environments for recreation, tourism, fishing, and ecosystem stability. By making ocean-monitoring tools more affordable and easier to deploy, the MANTARAY Profiler could help researchers gather more frequent data and improve understanding of local water conditions. This creates a connection between engineering design and the broader public good.

At the same time, technology should not be treated as a complete replacement for human judgment. The profiler has limitations, such as requiring GPS navigation at the surface and regular sensor calibration. These limitations must be communicated clearly to users so that the system is used responsibly and its data is interpreted correctly.

10.3 Civil Engagement

Civil engagement is an important part of the MANTARAY Profiler project because the system is intended to serve researchers, universities, and communities interested in understanding and protecting water environments. The project was shaped by stakeholder needs, including input from advisors, marine researchers, and potential users. These stakeholders helped define priorities such as ease of deployment, reliability, accurate data collection, and future reproducibility for student research teams.

The profiler has the potential to support communities that are affected by changes in water quality. For example, coastal communities, environmental groups, and research institutions could benefit from a lower-cost tool that collects data without requiring a large boat crew or expensive equipment. By helping make environmental monitoring more accessible, the project encourages broader participation in marine research and supports community-based environmental awareness.

Civil engagement also means considering who will use the data and how it may affect public decisions. Water-quality data can influence conservation efforts, policy discussions, and community responses to environmental problems. Because of this, the data should be collected, stored, and presented in a way that is transparent and understandable. Users should be able to know how the data was collected, what sensors were used, and what limitations may affect the results.

In the future, the project could be strengthened by involving more local stakeholders, such as coastal organizations, educational programs, and community science groups. This would help ensure that the profiler is not only technically successful but also useful to the people and communities it is meant to support.

10.4 Environmental Impact

The environmental impact of the MANTARAY Profiler is central to the project because the system is designed to support ocean health monitoring. One positive environmental impact is that the profiler could reduce the need for repeated boat-based data collection or diver-based surveys. Traditional methods can require more fuel, time, and human labor. A compact autonomous profiler can collect water-column data with less disturbance to the surrounding environment.

The profiler is also intended to improve understanding of water conditions by measuring dissolved oxygen, pH, conductivity, temperature, and depth. These measurements can help researchers identify environmental changes, monitor ecosystem health, and better understand how water conditions vary across locations and depths. In this way, the profiler supports environmental stewardship by giving researchers a tool to collect useful data more efficiently.

However, the system also introduces environmental risks that must be managed. Since the profiler uses batteries, electronics, sensors, thrusters, and sealed enclosures, the design must prevent leaks, battery exposure, or the vehicle from being lost in the water. The inclusion of internal monitoring sensors, such as leak detection and voltage monitoring, helps reduce this risk by allowing the team to identify problems before major damage occurs.

Another environmental consideration is minimizing disturbance to marine life. The profiler should be operated carefully in sensitive habitats and avoid unnecessary contact with animals, reefs, or the seafloor. Testing and deployment procedures should include responsible site selection, pre-deployment checks, and recovery planning. Overall, the project's environmental goal is to collect useful ocean data while minimizing the profiler's footprint on the ecosystem.

10.5 Economic Impact

The MANTARAY Profiler has an important economic impact because it is intended to provide a lower-cost alternative to traditional ocean-monitoring methods. Many existing underwater vehicles, commercial profilers, and boat-based research methods can be expensive, which limits access for smaller universities, student research teams, and community-based organizations. By focusing on a compact, modular, and lower-cost design, the MANTARAY Profiler could make environmental data collection more accessible.

Cost was also an important design constraint during development. The team had to balance performance with affordability when selecting sensors, communication systems, batteries, and mechanical components. For example, more advanced underwater communication or positioning systems could improve performance, but they were not realistic within the project budget. This required the team to make practical engineering tradeoffs while still meeting the main mission goals.

The system may also reduce operational costs for users. If the profiler can be deployed by a small team or a single trained operator, users may not need to rely as heavily on boats, divers, or large research equipment for routine water-column measurements. This could lower the cost of repeated monitoring and make it easier to collect data more often.

At the same time, the economic impact is not only about reducing costs. The profiler must also be reliable enough that users do not spend excessive time or money on repairs, troubleshooting, or repeated failed deployments. Maintenance requirements, sensor calibration, waterproofing checks, and battery management all affect the long-term cost of ownership. Therefore, future improvements should continue to focus on making the profiler easier to manufacture, maintain, and operate so it can become a practical tool for affordable marine research.

Chapter 11

Standards and Constraints

11.1 Constraints

11.1.1 Cost Constraint

A significant constraint in the development of the vertical profiler system is the project budget, which directly limits the selection of communication technologies. Ideally, advanced underwater communication systems such as GNSS-integrated acoustic positioning or Ultra-Short Baseline (USBL) systems would enable continuous, real-time communication between the profiler and the base station. However, these technologies are significantly more expensive and were not feasible within the allocated budget. These limitations are consistent with common constraints in embedded and underwater systems, where communication reliability and power efficiency are major design challenges. [1] As a result, the system relies on LoRa-based communication, which only allows data transmission when the profiler surfaces and is within a limited range of the transceiver. This introduces limitations in real-time monitoring, reduces communication reliability during underwater operation, and requires the system to incorporate fail-safe behaviors such as surfacing under error conditions.

11.1.2 Battery Constraint

A big constraint of the profiler and it's runtime is based on the voltage of the LiPo battery, as well as how many sensors are currently drawing power from it. LiPo battery constraints currently mention that having lower temperatures would increase the resistance which leads to a reduction in battery capacity. Currently, we believe that our profiler has enough time for a 2 hour continuous mission (in the water) with a 4 hour total runtime of power being continously drawn, but things such as thrusters not drawing it's max power. Because the profiler is operated fully off of one battery, it's constraint is extremely important because it has an impact on the active sensors, how long various sensors can remain active, and the ability for thruster and GPS navigation. As such, we need to find the combination that allows us to run for the longest time (currently 2 hours) by only using power when needed and keeping unnecessary sensors inactive as much as possible.

11.1.3 GPS Constraint

A significant constraint in the development of the MANTARAY profiler system is that the GPS cannot take in navigation information while the system is underwater and must be done at the surface. Since the system can't continously update it's navigation when submerged, if there are any extreme currents the profiler will not be able to take it into account. This limits the project because if the profiler drifts during it's vertical data collection segment of the mission, the profiler will not have a way to recognize this and self correct. As a result, our design must take into account this limitation as well as communicate this to our users.

11.1.4 Maintenance Constraint

Another major constraint is the maintenance requirement of the system's sensors and hardware components. The vertical profiler relies on multiple sensors, including orientation sensors, leak detection sensors, pH sensors, depth sensors, and oxidation/dissolved oxygen sensors. These components require periodic calibration and maintenance to ensure accurate data collection. For example, the orientation sensor must be recalibrated each time it is powered off and restarted, which introduces additional operational overhead and potential inconsistencies in navigation accuracy. Similarly, environmental sensors must be regularly checked and recalibrated every few weeks to maintain measurement precision. To mitigate this constraint, the system incorporates diagnostic indicators such as LED alerts for sensor malfunctions and structured data logging to identify calibration drift over time. However, maintenance remains a critical limitation affecting usability and operational efficiency.

11.2 Standards

11.2.1 ISO/IEC Python Programming Standard

The software components of the vertical profiler system, particularly those responsible for waypoint navigation, data processing, and error plot generation, are developed using the Python programming language. Python follows the ISO/IEC 30170 standard, which defines specifications for programming language structure, syntax, and interoperability. Adhering to this standard ensures that the system software is portable, maintainable, and compatible across a wide range of platforms and computing environments. Using a standardized programming language improves development efficiency and allows for easier debugging, testing, and future enhancements. Python's extensive ecosystem of libraries enables efficient implementation of data analysis and visualization tools, including trajectory error plots, waypoint accuracy graphs, and heading versus bearing comparisons. These features are critical for evaluating navigation performance and identifying system-level issues during testing. Additionally, compliance with ISO standards promotes consistency in coding practices, improves readability, and facilitates collaboration among developers. This is especially important in engineering projects where multiple contributors may work on the system over time. By following ISO/IEC standards, the software achieves a higher level of reliability, scalability, and long-term usability. [9]

11.2.2 IEEE Embedded Systems and Communication Standards

The hardware and embedded control system of the vertical profiler is implemented using Arduino-based microcontrollers, which follow widely accepted standards established by the Institute of Electrical and Electronics Engineers (IEEE). Communication protocols and interfacing methods used within the system align with IEEE standards such as IEEE 802.3 (Ethernet) and IEEE 802.15 (wireless communication frameworks), which define how data is transmitted and received reliably between devices. These standards play a crucial role in ensuring stable and efficient communication between system components, including sensors, microcontrollers, and external interfaces. Reliable communication is especially important in this project due to the challenges associated with underwater operation, where signal transmission is limited and prone to interference. By adhering to IEEE standards, the system benefits from improved interoperability between components, reduced integration complexity, and enhanced robustness in real-world conditions. Furthermore, IEEE standards provide guidelines for system design, testing, and validation, ensuring that the embedded system operates safely and efficiently. This helps minimize system failures, improves data accuracy, and supports consistent performance across multiple deployments. Overall, compliance with IEEE standards enhances the reliability and effectiveness of the vertical profiler system. [10]

11.2.3 Electrical Safety Low-Voltage Electronics

The hardware and embedded control system of the MANTARAY profiler is implemented using Arduino-based microcontrollers and Li-Po batteries which are all low voltage. Although these components operate at relatively low voltages, they still require careful protection from water exposure in order to maintain safe and reliable operation. As such, all electronics need to be safe from any water leakage which could create electrical hazards and short circuits. By preventing leakage, the epoxy seal ensures electrical safety while protecting the microcontrollers and battery from damage. In turn, this reduces the risk of short circuits, overheating, and potential fires. As such, the proper sealing of the profiler is essential not only for device performance, but also for ensuring the safe operation of the system during testing and deployment for the users and system both. [11]

11.2.4 Environmental Protection Due to the Clean Water Act

The Clean Water Act requires that all projects must be designed to ensure there are no additional pollutants or plastics released into the environment. For MANTARAY specifically, the system must be carefully constructed to avoid introducing any contamination into the surrounding water during operation. The main potential contaminants are: battery-related components, plastic and microplastic debris, and chemical sealants and adhesives. As such, the project must be sealed properly with no loose materials, including potential for battery leakage. To meet these requirements, the project uses a fully sealed housing made from acrylic tubing and epoxy. The acrylic tubing provides a durable and rigid outer barrier, while the epoxy is used to seal joints and openings to help ensure the enclosure remains watertight and secure. [12]

Chapter 12

Conclusion and Outlook

This chapter concludes the thesis by summarizing the MANTARAY Profiler project. It reviews the final system capabilities, discusses limitations, and identifies future improvements that could be made by later teams. The chapter also reflects on the overall value of the project as a foundation for continued autonomous ocean-monitoring development.

12.1 Conclusion

This thesis presented the design, implementation, and preliminary testing of the MANTARAY profiler, marking a significant milestone in the development of autonomous marine instrumentation. Over the course of this year, the project successfully transitioned from a conceptual architectural design to a fully realized physical prototype. A primary achievement of this work was the validation of the vehicle's flipping mechanism, a core concept that was successfully tested and proven viable. Furthermore, the foundational navigation architecture was established and independently verified prior to the main chassis, while the onboard sensor suite underwent rigorous integration testing to ensure seamless connectivity and data cohesion. The shift toward AUVs represents the necessary future of oceanography.

Beyond the clear advantages in operational efficiency, mobility, and range, adopting platforms like the MANTARAY profiler directly addresses critical safety concerns in the field. Traditional data collection via scuba diving exposes researchers to volatile, inherently dangerous, and potentially life-threatening underwater environments. Replacing or supplementing human divers with autonomous profilers entirely mitigates these risks. While the milestones achieved this year provide a robust proof of concept, they represent just the beginning of the MANTARAY profiler project. Future work will focus on full system integration, localized field testing in open-water environments, and the optimization of autonomous path-planning algorithms. Ultimately, the MANTARAY platform stands poised to offer the scientific community an unprecedented tool for scalable, continuous, and lower-risk marine data acquisition.

12.2 Future Outlook

The primary objective of this year's scope was to construct a functional prototype to validate the feasibility of a shifting-mass actuation concept for pitching and flipping operations. While physical testing confirmed the viability of this core mechanism, several subsystems require systematic optimization and evaluation in future iterations.

Mechanical System Optimization

While the baseline prototype demonstrated initial mechanical success, resolving long-term waterproofing and tolerance issues remains critical. Although no water ingress was observed during final laboratory testing, future designs should integrate commercial off-the-shelf (COTS) marine components, such as Blue Robotics enclosures, to guarantee hydrostatic sealing. The custom aluminum fixtures manufactured to couple the end caps can be eliminated if precision-machined, manufacturer-matched tubes and enclosures are utilized. Strict component tolerancing is vital for deep-submergence applications. Leveraging integrated solutions, such as Blue Robotics' modular coupler flanges, ensures robust, high-tolerance, watertight assemblies. Consequently, future work should transition the vehicle's hull and internal lead screw assemblies to a standard 4-inch diameter form factor to match these modular coupling ecosystems. Additionally, the mass-shifting mechanism should be upgraded by incorporating underwater magnetic switches or Hall-effect sensors. Relying solely on open-loop, time-based actuator commands introduces positioning drift over time; a closed-loop limit-switch architecture provides definitive feedback when the drive nut reaches its linear thresholds. This hardware addition will guarantee that both shifting masses remain perfectly synchronized at the end of each cycle. Alternatively, a single-actuator differential mechanical linkage could be engineered to drive both lead screws simultaneously, inherently preventing synchronization errors. Finally, the internal chassis layout requires ergonomic and structural refinement. Future iterations must establish a streamlined battery-swapping mechanism, improve cable routing, and implement an external data port for tethered programming. The current enclosure assembly methodology, which relies on a mallet to seal the end caps and requires a vacuum seal, takes a bit of time. A mechanical locking ring or flange-bolt pattern should be investigated to facilitate seamless assembly and disassembly.

Navigation, and Control

While individual navigation algorithms were verified independently, full system integration within the physical vehicle remains to be tested. Future milestones must focus on full-scale, in-water closed-loop navigation trials. The current RF antenna array must be evaluated to optimize surface communication throughput. Concurrently, empirical characterization of thrust is required to refine the vehicle's rotational plant model and precisely map its mass moment of inertia. Further hydrodynamics testing must evaluate whether differential thrust alone provides sufficient yaw authority on the water surface, or if the addition of control surfaces (fins) or auxiliary maneuvering thrusters is mandatory. Additionally, the mission control protocol and its integration into the Graphical User Interface (GUI) must be fully developed. The current system relies on one-way simplex communication, in which waypoints are uploaded prior to deployment, and the vehicle calculates its trajectory using onboard GPS. However, operators lack real-time telemetry on the vehicle's operational state, spatial coordinates, pitch orientation, or fault-detection metrics (such as internal leak detection or collision alerts). Upgrading the communications architecture to a duplex (two-way) acoustic or RF telemetry link is critical for mission monitoring, real-time data streaming, and reliable asset retrieval.

Sensor Integration

While sensor communication protocols and data-fusion pipelines have been successfully validated, their ruggedized physical mounting brackets remain unbuilt. Future work must design low-drag, external sensor harnesses and optimize internal wire management. Transitioning from discrete point-to-point wiring to a centralized, custom Printed Circuit Board (PCB) routing shield should be explored to minimize electromagnetic interference (EMI) and reduce system failure points.

Power and Mission Simulation

The basics for power have been done and calculated; however, this needs to be verified. System testing, either through water tests or dry tests, to determine the amount of energy used in completing one waypoint, needs to be done. A procedure to check this also needs to be created.

12.3 Final Thoughts

Developing an underwater platform has been an incredibly rewarding endeavor. Operating in a marine environment introduces unique engineering constraints, forcing the team to develop simple, elegant, and unconventional solutions. Water is an unforgiving medium; its corrosive nature and hydrostatic pressures mean that the same environment we seek to explore possesses the inherent power to compromise mechanical and electrical integrity. While completing a fully autonomous profiler is achievable, success demands meticulous attention to technical detail and tight interdisciplinary collaboration. As the project transitions into its next critical phases of system integration and field implementation, maintaining rigorous documentation, synchronized design sessions, and transparent timeline management across the team remains vital. The team expresses its deepest gratitude to the Robotic Systems Laboratory (RSL)

for generously providing the specialized resources, technical wisdom, and structural guidance necessary to advance this project. This physical build was not realized without the support of our advisors. We are incredibly grateful for the opportunity to pioneer a platform that makes a tangible, positive impact on oceanographic research. While the MANTARAY profiler's development lifecycle remains incomplete, we take great pride in the foundational milestones achieved this year and recognize the continued evolution of this platform.

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Appendix A: Hazard Assessment Form

Attached below is a copy of our hazard assessment form submitted to the School of Engineering.

Student Project Hazard Assessment

A Hazard Assessment is designed to help students and project advisors recognize hazards associated with student projects at the early planning stages to find ways to minimize the chance of injury, loss, or harm while students are working on the project. A detailed assessment will also prevent the potential for project interruption due to unanticipated safety issues. This form is intended for projects where the primary hazards are associated with engineering work (physical, mechanical, electrical, etc.). Chemical and biological focused projects require a separate project assessment form.

Each student project must complete a Hazard Assessment form, even if the project is not expected to have any hazards. All required approvals must be obtained before proceeding with the project. It is important that all team members participate in the process, with close supervision of your advisor. To help ensure that hazards and risks associated with your project are not overlooked or underestimated, you are encouraged to contact additional university staff (lab directors/managers, EHS, etc.) with relevant knowledge or experience for guidance.

The Hazard Assessment process usually involves these five steps below, with an example:

Step:	Example:
1. Identify the specific tasks that must be completed to reach your project goals	One of your project tasks involves testing a live electrical circuit
2. Determine if there are hazards associated with completing the tasks	On the form, you select the "Electrical parts and assemblies > 50V or high current", under the Hazardous Conditions/Processes/Activities, Electrical Hazard section
3. If hazards exist, identify the risks connected with the hazards of each task. Ask yourself, what could go wrong? If you are not already familiar with the risks, do a quick internet search	After some research, you learn that there is potential of electrical shock from accidental contact with exposed live components
4. Develop a list of controls (things you can do) to eliminate the hazard or reduce the risks. Refer to Hierarchy of Controls on the next page	To minimize the risk identified above, you could: o De-energize and isolate the system <u>or</u> o Guard live components to prevent accidental contact

5. Create a safe working procedure. Describe how you will safely complete each task	You write a detailed procedure for testing a live electrical wire, that includes all the information from your hazard/ risk assessment and which controls you will use to reduce the risks
6. Submit your hazard assessment form for approval (see section below for details)	

Definitions

A hazard is something that has the potential to cause harm (injuries, accidents, or other undesirable effects). Hazards can be eliminated but not reduced. A hazard can be in the form of an agent, condition, process or activity.

Risk is the likelihood or probability of a hazard causing harm to people, property, or the environment. Risks associated with a hazard can be reduced. Put another way,

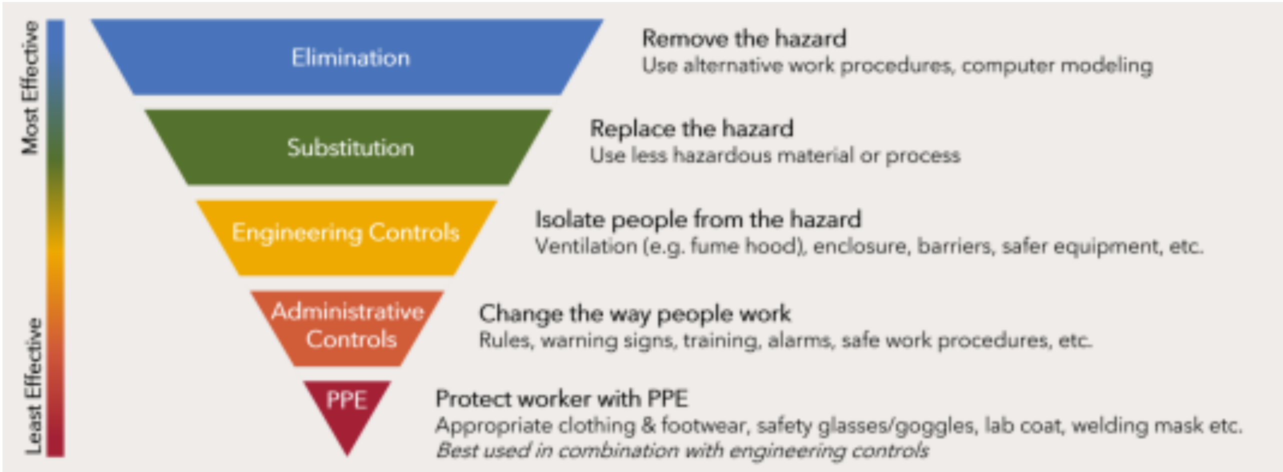
Risk = Hazard x Exposure

A hazard assessment is the process of identifying anything that can cause harm (hazardous agents, conditions, processes or activities). A risk assessment is the process of determining how great the chance is of harm occurring from a given hazard.

Hierarchy of Controls

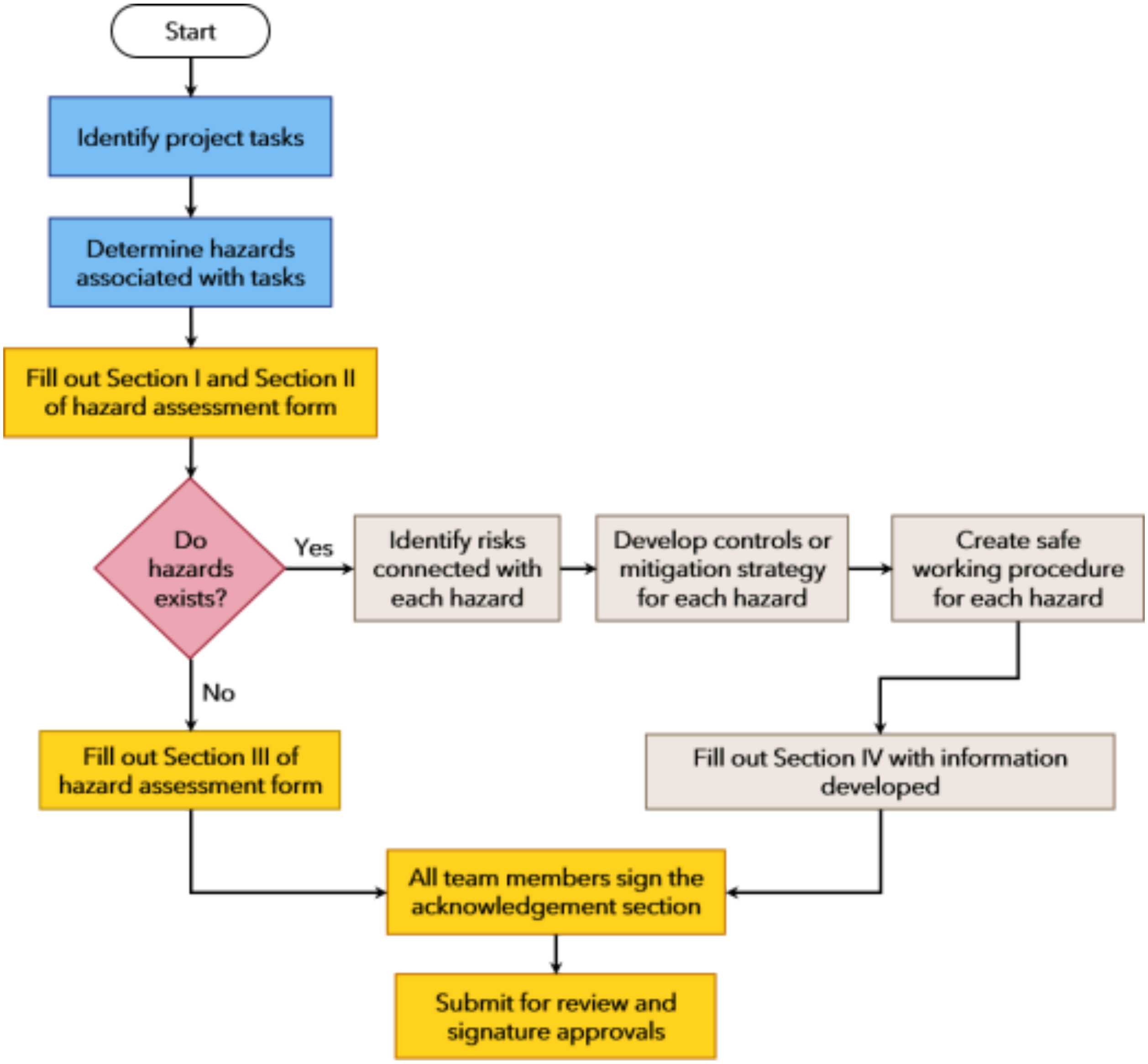
Unless the hazardous agent, condition, or activity is removed, hazards cannot be eliminated. However, risks from the hazard can be minimized by employing the proper control measures and safe work practices that will have been identified from completing a hazard assessment.

Some controls are more effective than others at eliminating hazards or reducing risk. Use the hierarchy of controls chart below to evaluate the controls measures you plan to use. Priority should be given to the most effective controls at the top of the hierarchy (elimination and substitution) and moving down, rather than start with the easiest one. While personal protective equipment (PPE) should always be used, it should be considered the last line of defense from potential hazards.



Revised Sept 2025 scu.edu/ehs 2

Hazard Assessment Form Process



1. After completing the form, all team members must sign the acknowledgement section.
2. Your advisor and the department chair must approve this form prior to obtaining formal approvals from other university staff.
3. If your project involves the use of lab or shop space or equipment, the form must be routed to the appropriate lab/shop manager(s) for review and approval.
4. Your faculty advisor or department chair will make the determination whether EHS approval is additionally required.

Depending on the scope of your project, the faculty advisor, department chair, lab/shop manager(s), or EHS may request further approval from other relevant faculty, staff, or department.

This form is to be used for student projects where primary hazards are associated with engineering work (physical, mechanical, electrical, etc.). Chemical and biological focused projects require a separate form.

Complete this form and obtain all the required approvals (Faculty Advisor, Department Chair, Laboratory Manager, EHS, etc.) before proceeding with the project. Please refer to the hazard assessment guide for assistance in filling this form.

SECTION I: Project Description

Project Title: MANTARAY
Project Team Members: Divya Bengali Ashika Balamurugan Gabby Ruiz Ysidro Magana Angelina Ekdawy Alondra Valencia Alexander Torres
Project Faculty Advisor: Michael Neumann Name: Department: Mechanical Engineering Phone: 554-5275 Email: maneumann@scu.edu
Proposed Project Location(s) (Department, building, room#): RSL: SCDI 1205
Anticipated Dates of Project Duration: 09/22/25-06/19/26
Summary of Project Objectives: Design and deliver an AUV profiler that autonomously transits between specified stations at the surface, performs depth-resolved vertical profiles, and is capable of seamless flips in orientation. The system will provide ocean-health monitoring by logging temperature, conductivity/salinity, and depth. Initial operating depth level target 30ft near-shore missions, ≥2 hours endurance, positive buoyancy and retrieval features for safe recovery, and a modular payload bay for rapid sensor swaps.

SECTION II: Hazard Checklist

Identify all the tasks that must be completed for your project. Carefully evaluate each task to determine if there are any associated hazards. After identifying the hazards of your project, you will be asked to assess the risk connected to each hazard and to identify control measures that will either eliminate the hazard or reduce the risk to an acceptable level. Safe work procedures for each step involving a known hazard will need to be developed.

HAZARDOUS CONDITIONS / PROCESSES / ACTIVITIES
☑ Batteries ☑ Power Tools & equipment ☑ Machine guarding/power transmission: gears, rotors, wheels, shafts, belt/chain drives, rotating parts, pinch points ☑ Robotics ☑ Sharp Objects ☑ Material handling of heavy objects

Hazard Checklist (continued)

HAZARDOUS AGENTS
Physical Hazards of Chemicals ☑ Explosives ☑ Flammables

SECTION IV: Hazard Assessment and Control

Description of Potential Hazards

Provide a summary of the procedure and describe the risks associated with each hazard that you have identified above or on the previous page. Use one box below per hazard. You may add additional pages if needed. Define the hazard control measures that will be employed to minimize the risks based on the hierarchy of controls (elimination, substitution, engineering controls, administrative controls, PPE), and then describe specific control measures you will use (e.g. work on system de-energized, receive hazard specific training, shield hot surfaces, guard pinch points, relieve stored energy, wear protective equipment, use less hazardous chemical, etc.). Refer to "Hierarchy of Controls" in the instructions sheet for more information to decide which hazard controls measures are most appropriate.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Manufacturing
Summary of Procedure or Tasks: Many of our components for assembly will need to be machined. Such as drilling, cutting, and facing.

Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): Machine shop equipment presents significant injury risks if misused or if equipment is faulty. Common hazards include entanglement from high-RPM rotating tools (drills, mills, lathes), where loose clothing, jewelry, lanyards, or unsecured long hair can be drawn into moving parts, causing severe injury. Operators will be exposed to metal chips, cutting oil, and fumes which could cause injury if PPE is not worn.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): Only certified student operators may use the shop, and no one works alone. All activities follow posted SOPs and SCU safety rules (Machine Shop, Maker Lab, RSL SCDI 1205; Alameda 3305). Before use, machines are inspected, guards verified, emergency stops checked, and only one person operates a machine at a time (never work alone)with proper workholding. Required PPE (ANSI safety glasses, closed-toe shoes, long pants and hearing/face protection as needed) is worn; long hair is tied back and all loose clothing, jewelry, and gloves near rotating tools are prohibited.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Electrical Components
Summary of Procedure or Tasks: We will be assembling and adding electrical components inside the profiler. Such as microcontrollers, sensors (temperature, acidity, turbidity, depth, pressure, etc.), motors (thrusters). Which requires soldering and manual wiring.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): If the electrical components are not handled properly it can lead to fires, explosives, or electrocution. Soldering components together or using any type of heat gun could potentially cause harm or burn if used without proper training.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): Before any work begins, electrical components such as sensors are inspected for damage and batteries are removed so the assemblies are unpowered. While assembling, no electrical component may be connected to a power source. Everyone must wear appropriate PPE at all times. All electronics are handled only in a dry, clean, and well-organized workspace to minimize the risk of electrical shorts. All team members have also undergone soldering training with only lead-free solder and fume extractors being used.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Use of Power Tools
Summary of Procedure or Tasks: Power tools will be required during profiler assembly for tasks such as installing thrusters, assembling the electronics enclosure, and sealing the endcaps.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): Working with motorized tools carries inherent injury hazards. Loose or dangling clothing increases this risk, as it can be cut or become entangled, leading to injury or even death.

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): All activities will adhere to Maker Lab procedures, MECH 101L guidelines, and RSL training requirements. At all times, personnel must wear PPE safety glasses, long pants, and closed-toe shoes and anyone with long hair must keep it tied back. A brief review of power-tool safety protocols will be conducted prior to use. Only students who have the appropriate training in MakerLab, 101L will be allowed to use power tools.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Electrical Components in/near water
Summary of Procedure or Tasks: Because the profiler will be operated in close proximity to water (both before and during use), the pressure tube must be inspected for any air leaks to ensure watertight integrity. Additionally, set up the base-station equipment in a secure, dry location to avoid electrical shorts.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): If the profiler is not properly sealed it can lead to exposure to water and can lead to short circuiting and could damage the electronics.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): Electronics will have waterproof cases to mitigate risk, we will conduct repeated leak checks before field operations and perform a final inspection immediately prior to launch. All seals will be verified and we'll carry spare O-rings/gaskets for rapid replacement. The base station will be set up on dry, elevated ground to keep electronics clear of spray and splashes. After each recovery, the AUV will be shut off and will be thoroughly dried with towels before any access to electrical compartments to reduce shock hazards.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Thrusters
Summary of Procedure or Tasks: Thrusters spin at a high rpm when the profiler is in operation.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): The thrusters could catch onto nearby objects such as fingers, jewelry, hair, or strands. This can lead to serious injury risks and physical damage.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): The deploying student must wear safety glasses, gloves, long pants, and closed-toe shoes. All team members will secure long hair and remove loose clothing or accessories during field work to prevent entanglement. Testing will follow written procedures with a two-person check for completeness and safety. Thrusters will receive a visual inspection prior to deployment/testing. Before we power-on the thrusters a clear verbal call-out will be made so everyone is aware that the propellers may begin spinning.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Retrieval of Profiler

Summary of Procedure or Tasks: The AUV will be operated in water. Possible retrieval spots depending on deployment could be from a boat, dock or shoreline.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): If the profiler gets caught in a stream or starts flooding we risk losing it. If the battery runs out or loses connection we could lose the profiler. The profiler could get tangled or collide with the boat's propellers causing damage to the boat and the profiler. Another hazard is also that a person could fall into water while trying to lift the profiler out of the water
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): The profiler will have a leak sensor to detect any water entering the electrical or main components and a battery is low alert which will notify the user. We will also confirm the vehicle is positively buoyant so it will surface and remain afloat if power or control is lost. To aid recovery in low-visibility conditions, equip the profiler with high-intensity strobe beacons for visual tracking. For retrieval we will aim the profiler to a spot far away from the boat and approach it with low speed. To prevent people from falling into the water there will be a handle on the profiler so it can easily be handled and lifted. Retrieving the profiler will require at least two people capable of lifting its weight.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Boat Safety/water safety
Summary of Procedure or Tasks: We may be using a boat to test our profiler or we will be testing from the shore/dock.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): Risks of falling overboard, drowning, coming into contact with the propellers at the stern which could result in serious injuries. For dock and shore deployments there are risks of falling into the water trying to deploy and retrieve the profiler.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): Boat operations will be run by an experienced captain with a California Boater Card (or equivalent). We will follow all California open-water rules. Life jackets will be worn as required by conditions and policy, and the captain is in charge from leaving the dock to return. Before the first deployment, all students will complete the ENGR 180 (Marine Operations) Camino safety and emergency modules. Students will work together (2 people) to deploy and retrieve the profiler to minimize risk of falling off the boat or dock.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Usage of LiPo batteries & transportation/Disposal
Summary of Procedure or Tasks: The profiler will contain LiPo batteries when it is deployed. We will be transporting and using LiPo batteries when we are traveling to deploy our profiler.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk):

LiPo batteries pose a risk of heating up, swelling, catching fire, and bursting if they are not used, stored, or transported properly. Also could pose a risk of chemical leakage, or environmental contamination if not disposed of properly.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): LiPo packs will be transported in fire-resistant LiPo bags inside RSL ammo boxes and inspected before and after use. Pack voltage per battery should be 14.8 V each and checked for individual cell balance this will be verified per ENGR 180 procedures. Damaged batteries will be removed from service, and fire extinguishers and sand will be on hand during handling/charging. For disposal, batteries will be fully discharged and taken to an approved recycling facility, with personnel trained on proper disposal steps.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): AUV weight
Summary of Procedure or Tasks: The AUV will weigh less than 50lbs and will require students manually to lift it and drop the AUV in and out of water, boats, shores, or docks.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): Since the AUV will be heavy, students could strain or injure themselves if the AUV is too heavy for them. This could result in straining their back or other muscles. If not careful the AUV could also fall onto someone and seriously injure them. It could also damage the components of the AUV.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): We will be using a cart to transport the AUV and the AUV will be transported by 2 or more people who are comfortable lifting with proper form if the cart is inaccessible. Students must wear closed-toed shoes when transporting the AUV and students should not have any body parts directly underneath the AUV in case the AUV slips and falls. Students will communicate when transporting the AUV.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Component Safety
Summary of Procedure or Tasks: The AUV will be transported to deployment zones and for testing.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): If not stored properly and carefully the components such as thrusters, sensors, etc could be damaged or fail to work. This could raise the risk of electrical shock or a broken AUV.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): AUV will be stored in a secure spot when transporting making sure it is tied down and unable to move around. Some components may be taken apart if they pose a big risk of getting damaged and secured somewhere else that prevents any damage. Components will be checked before and after transportation.

SAFETY EQUIPMENT and PPE

Select the appropriate PPE and safety supplies you will need for the project (Check all that apply)

- ☑ Appropriate street clothing (long pants, closed-toed shoes)
- ☑ Gloves; indicate type: Work
- ☑ Safety glasses/ goggles
- ☑ Fire extinguisher

TRAINING REQUIREMENTS

Identify the appropriate training (check all that apply)

- ☑ Electrical Safety for Engineering Camino Course – contact EHS to enroll
- ☑ LiPo Battery Safety Training – contact MAKER Lab to enroll
- ☑ Laboratory Specific Training – contact Lab or Shop Manager/Director
- ☑ Project Specific Training – contact Faculty Advisor

EMERGENCY PROCEDURES

Life-threatening emergencies (police, fire, explosion, hazardous material spill/release, gas leak, etc.)

1. Call or text 911, then call SCU Campus Safety at 408-554-4444
2. Alert people in the vicinity and if necessary, activate the local alarm systems
3. Evacuate to your emergency assembly point (EAP). Fill in your EAP here: "In case of building evacuation, personnel in SCDI 1205 should proceed to the Northwest corner of the building near the fountain on the Sobrato mall."
4. Remain nearby to advise emergency responders

For medical emergencies:

1. Stay with the individual if it is safe to do so. Do not move the individual unless absolutely necessary 2. Call SCU Campus Safety or 911
3. Administer first aid if you are trained to do so

If person received an electrical shock:

1. Do not touch the person
2. Shut off power and/or rescue the person with a non-conductive object IF it is safe to approach 3. Call SCU Campus Safety or 911
4. Administer CPR or AED if trained to do so

If person exposed to hazardous materials:

1. Flush contamination from eyes/skin using the nearest emergency eyewash/shower for at least 15 minutes. Remove any contaminated clothing
2. Call SCU Campus Safety or 911

For building maintenance emergencies (power outages, plumbing leaks etc.): call Facilities 408-554-4742

REPORT all injuries and incidents (including near misses) to faculty advisor and EHS
Project work outside of SCU campus

Generally, all project work must be performed at SCU campus. However, there may be few cases where work cannot be completed on campus (e.g. competition venue outside of SCU, no appropriate campus location to field-test). These exceptions must be described in the hazard assessment section above. Specific location(s) and their scope of work must have approval from the faculty advisor. Additional approvals may be required.

Check the appropriate project location scope:

All project work cannot be completed on SCU campus. Provide more details below:

List offsite location(s) and provide description:

- ☐ Test Tank at MBARI- Address: 7700 Sandholdt Rd, Moss Landing, CA 95039. MBARI is a nonprofit center focused on oceanographic research. The test tank is an indoor salt water tank (~35 feet) and will be supervised by staff.
- ☐ Bethany Reservoir- Address: 13638 Christensen Rd, Byron, CA 94514. This is a local reservoir where we will be able to go and test the profiler in more realistic conditions to ensure it works in a local environment outside of a test tank. We will use one of the RSL's boats for testing.
- ☐ Monterey Bay- This is a local bay where we will be able to go and test the profiler in more realistic conditions to ensure it works in a local environment outside of a test tank. A boat will be rented by the RSL for testing.
- ☐ Alviso Boat Ramp - Address: 1195 Hope St, Alviso, CA 95002. The ramp will be used for initial field testing from the shore. This will be used to test the flipping maneuver of the profiler.

Describe supervision arrangements and emergency procedures for each offsite location:

- One of our advisors will be with us during all work completed outside of SCU campus.
- MBARI: An advisor will be present during the duration of our time testing at MBARI to ensure rules are followed and in the event of an emergency, they can guide us as needed. A student will be given the task to ensure all safety rules are followed in accordance with both MBARI and SCU.
- Monterey Bay: Monterey Bay boat captain/dive master appointed for our boat will be with us during the entirety of our deployment to ensure safety protocols are followed and alert us ahead of time for any emergency plans needed. A student will be given the task to ensure all safety rules are followed in accordance with both MBARI and SCU.
- Bethany Reservoir: For the duration of our deployment, an RSL staff member will captain the boat and supervise to ensure all safety requirements are being followed. A student will be given the task to ensure all safety rules are followed in accordance with both Bethany Reservoir and SCU. The previous will also be used for any testing at the reservoir without the boat in order to test the flipping mechanism of the profiler.
- Alviso Boat Ramp: An advisor will be present to guide us through the safety procedure and assist in the event of an emergency. A student will be given the task to ensure all safety rules are followed in accordance with SCU.

ACKNOWLEDGEMENT

By signing, I verify that:

1) I am aware of the hazards and risks of all the tasks associated with the project 2) I have received, or will receive all the necessary safety training, have read the safety manual and/or safety data sheets (SDSs) relevant to the project before performing any hazardous tasks.

3) I will follow all required safety precautions while working on this project, including but not limited to use of engineering controls, following safe work practices, and wearing appropriate personal protective equipment, as well as all emergency procedures

Name of Project Team Member	Signature	Date
Ysidro Magana		10/15/2025
Alondra Valencia Prado		10/15/2025
Alexander Torres		10/15/2025
Ashika Balamurugan		10/16/2025
Divya Bengali		10/17/2025
Angelina Ekdawy		10/20/2025
Gabriela Ruiz	Gabriela Ruiz	10/20/2025

APPROVALS

This document must be reviewed and approved, in the order listed below, before any project work can begin. A copy of the approved document must be kept with the project team.
1. Faculty Advisor (required)
Name: Department: Signature Date
2. Department Chair (required)
Name Signature Date
3. Laboratory Director/Manager (required if project involves use of lab or shop space)
Name Signature Date
4. EHS (required as determined by faculty advisor, department chair, or lab director/manager)
Name Signature Date
5. Other (if requested by faculty advisor, department chair, lab director/manager, or EHS)
Name Signature Date

Appendix B: Bill of Materials

Attached below is a copy of our bill of materials submitted to the School of Engineering. The links to the purchased materials are hyperlinked to the name.

Name	Category	Quantity	Unit Cost	Cost
Led Lights	*Hardware*	*12*	*$19.04*	*$228.48*
T200 Thruster with Penetrator (BlueROV2 Spare)	Hardware	4	$268.80	$1,075.20
Selection Choice: Electronics Tray Terminal Blocks and Hardware.	Hardware	1	$153.64	$153.64
Leak Sensor	Hardware	2	$32.99	$70.00
Buck Converters	Electrical equipment	5	$8.50	$42.50
Arduino Mega	Electrical equipment	2	$22.99	$45.98
Voltage Sensor	Hardware	2	$5.99	$11.98
Lithium Ion Batteries	Hardware	2	$360.00	$720.00
I^2C Level Converter	Electrical equipment	1	$30.00	$60.00
Acrylic Tube	Hardware	1	$540.00	$540.00
Conductivity Sensor	Hardware	2	$109.99	$219.98
pH sensor	Hardware	2	$319.99	$639.98
Pressure sensor	Hardware	2	$90.00	$180.00
Disolved Oxygen sensor	Hardware	2	$329.99	$659.98
Wires	Hardware	2	$6.98	$13.96
ESC	Hardware	4	$40.00	$160.00
GPS	Hardware	2	$29.95	$59.90
T-slot rails	Building material	2	$16.08	$32.16
U-Bolt	Building material	1	$35.19	$35.19
Desicant	Hardware	1	$14.00	$14.00
PLA Filament	Building material	4	$30.00	$120.00
End caps	Building material	2	$110.00	$220.00
Switch Penetrators	Hardware	2	$28.00	$56.00
Pressure Valve	Hardware	2	$3.84	$7.68
			Totals	**$5,366.61**

Appendix C: Scripts

Combined Industrial pH and Temperature Sensor Code

This appendix includes Arduino code used for communication with the Atlas Scientific pH and temperature sensor circuits. The code was written for an Arduino Mega 2560 or similar board and uses UART communication. In this setup, the pH sensor communicates through Serial3, while the RTD temperature sensor communicates through Serial2.

Listing 1: Arduino code for combined pH and temperature sensor readings.

```
// Combined Industrial pH + Temperature Sensor Code
// Atlas Scientific EZO circuits using UART
// pH on Serial3, RTD temperature on Serial2
// Written for Arduino Mega 2560 or similar boards

String inputstring = "";
String sensorstring_ph = "";
String sensorstring_temp = "";

float pH = 0.0;
float temperature = 0.0;

unsigned long lastRequest = 0;
const unsigned long interval = 3000;  // 3 seconds between readings

void setup() {
  Serial.begin(9600);    // USB Serial for monitor
  Serial2.begin(9600);   // RTD temperature sensor
  Serial3.begin(9600);   // pH sensor

  inputstring.reserve(10);
  sensorstring_ph.reserve(30);
  sensorstring_temp.reserve(30);

  Serial.println("Atlas Scientific pH + Temperature Interface");
  Serial.println("------------------------------------------------");
  Serial.println("pH on Serial3, RTD on Serial2");
  Serial.println();
}

void loop() {
  // Manual command passthrough
```

```
if (Serial.available()) {
  inputstring = Serial.readStringUntil('\r');
  inputstring.trim();

  if (inputstring.startsWith("PH")) {
    Serial3.print("R\r");   // manual read pH
  }
  else if (inputstring.startsWith("RTD")) {
    Serial2.print("R\r");   // manual read temperature
  }
  else {
    Serial.println("Commands:");
    Serial.println("  Type 'PH' for pH reading");
    Serial.println("  Type 'RTD' for temperature reading");
  }

  inputstring = "";
}

// Automatic sensor reads
if (millis() - lastRequest > interval) {
  Serial3.print("R\r");   // request pH
  Serial2.print("R\r");   // request temperature
  lastRequest = millis();
}

// Read pH response
if (Serial3.available()) {
  sensorstring_ph = Serial3.readStringUntil('\r');
  sensorstring_ph.trim();

  if (sensorstring_ph.length() > 0 && isdigit(sensorstring_ph[0])) {
    pH = sensorstring_ph.toFloat();
    Serial.print("pH: ");
    Serial.println(pH);
  }

  sensorstring_ph = "";
}

// Read temperature response
if (Serial2.available()) {
  sensorstring_temp = Serial2.readStringUntil('\r');
  sensorstring_temp.trim();

  if (sensorstring_temp.length() > 0 &&
      (isdigit(sensorstring_temp[0]) || sensorstring_temp[0] == '-')) {
    temperature = sensorstring_temp.toFloat();
    Serial.print("Temp C: ");
    Serial.println(temperature);
  }
```

```
    sensorstring_temp = "";
  }
}
```

IMU Heading Test Code

This script was used to test the BNO055 inertial measurement unit and read the profiler's heading. The yaw value from the IMU was printed to the serial monitor and used to understand the profiler's current orientation.

Listing 2: Arduino code for reading heading from the BNO055 IMU.

```
// Use IMU to determine the profiler heading

#include <Wire.h>
#include <Adafruit_BNO055.h>
#include <utility/imumaths.h>

Adafruit_BNO055 bno = Adafruit_BNO055();

void setup() {
  Serial.begin(115200);

  if (!bno.begin()) {
    Serial.println("BNO055 not detected");
    while (1);
  }

  Serial.println("BNO055 detected");
}

void loop() {
  imu::Vector<3> euler = bno.getVector(Adafruit_BNO055::VECTOR_EULER);

  // Variables needed for heading
  float yaw   = euler.x();
  float roll  = euler.z();
  float pitch = euler.y();

  Serial.print("Yaw: ");
  Serial.println(yaw);

  delay(100);
}
```

GPS Waypoint Bearing Code

This script was used to read GPS data and calculate the desired bearing from the profiler's current location to a target waypoint. The desired bearing indicates the direction the profiler should point to navigate toward the waypoint.

Listing 3: Arduino code for GPS waypoint bearing calculation.

```
// Use the GPS location to figure out where the profiler needs to point

#include <Adafruit_GPS.h>
#include <SoftwareSerial.h>
#include <math.h>

#define GPSSerial Serial1

Adafruit_GPS GPS(&GPSSerial);

// Position variables: latitude and longitude
float currentLat = 0.0;
float currentLng = 0.0;

// Waypoint variables: target latitude and longitude
float targetLat = 37.335;
float targetLng = -121.881;

float desiredBearing = 0.0;
float distanceToWaypoint = 0.0;

void setup() {
  Serial.begin(115200);
  GPSSerial.begin(9600);

  GPS.begin(9600);

  // Only request RMC and GGA sentences
  GPS.sendCommand(PMTK_SET_NMEA_OUTPUT_RMCGGA);

  // Set update rate to 5 Hz for navigation
  GPS.sendCommand(PMTK_SET_NMEA_UPDATE_5HZ);

  delay(1000);

  Serial.println("GPS Initialized");
}

void loop() {
  char c = GPS.read();

  if (GPS.newNMEAreceived()) {
    if (!GPS.parse(GPS.lastNMEA())) {
      return;
    }
  }

  if (GPS.fix) {
    // Update the current GPS position
    currentLat = GPS.latitudeDegrees;
```

```
    currentLng = GPS.longitudeDegrees;

    updateNavigation();

    // Print the bearings
    Serial.print("Desired Bearing: ");
    Serial.println(desiredBearing, 2);
  }
}

void updateNavigation() {
  // Planar bearing calculation: theta = atan2(delta_x, delta_y)

  // Compute the difference between the waypoint and the current position
  float dLat = targetLat - currentLat;
  float dLng = targetLng - currentLng;

  // Convert degree differences into meters
  // East to West and North to South errors
  float x = dLng * 111320.0 * cos(radians(currentLat));
  float y = dLat * 110540.0;

  // The desired bearing
  desiredBearing = degrees(atan2(x, y));

  // Convert from -180 to 180 range into 0 to 360 range
  if (desiredBearing < 0) {
    desiredBearing += 360;
  }
}
```

Appendix D: Calculations

Weight and Balance Sheet and Center of Gravity Calculations

Component	Weight in Air (kg	Weight in Water	Displacement (m	F_B (N)	Quantity	Height/Length (n	Width/Radius (m	Thickness (mm)	
Battery	1.116	0.503	1262277	12.69	2	145.999	37.09	74.19	
Thruster	0.427	0.236	2613613	26.27	3	113.03	49.53	44.45	
Tube	0.138	0.0218	116240	1.17	1	914.4	IR:63.50 OR:69.85		
End Cap	0.393	0.0522	231640	2.33	2	9.14	63.5		
O Ring	0.238	0.0322	2277	0.0229	2	28.01	IR:65.23 OD:68.83		
Rails	0.0675	0.0632	8712	0.0876	2	858.38	3.33		
Electrical Tray	0.311	0.0105	262193	2.64	4	6.35	101.6		
Electrical Compo	0.567	0.157	69643	0.7	1	215.9	101.6	3.18	
3D Parts	1.814								
T Rails	0.821	0.508	304000	3.06	3	838.2	19.05	19.05	
Antenna	0.113				1				
Sum	6.0055								

Figure 1: Weight and balance sheet.

Item	CG from Top (mr	Mass Each (kg)	Qty	Total Mass (kg)					I(z)
Battery 1	841.25	1.116	1	1.116		**Total Mass**			1705.216529
Battery 2	694.94	1.116	1	1.116		9.433	kg		1541.934569
Thruster 1	889.64	0.427	1	0.427		**Xcg**			903.6389422
Thruster 2	889.64	0.427	1	0.427		7355.751549			903.6389422
Thruster 3	889.64	0.427	1	0.427					903.6389422
Tube	457.2	0.138	1	0.138					0
End Cap 1	4.57	0.393	1	0.393					794.133135
End Cap 2	909.83	0.393	1	0.393					1149.900315
O-Ring 1	14.01	0.238	1	0.238					0
O-Ring 2	900.39	0.238	1	0.238					0
Rail (x2)	429.19	0.0675	2	0.135					0
Electrical Tray	304.8	0.311	4	1.243					0
Electrical Compo	304.8	0.567	1	0.567					0
Antenna	457.2	0.113	1	0.113					0
T Rail (x3)	419.1	0.821	3	2.463					833.3333333
				9.434					0
									\

Figure 2: X center of gravity calculation.

Item	ZCG w Batteries Lower (mm)	ZCG w Batteries Center (mm)	Mass (kg)	I x - Column B (mm^4)	I x - column C (mm^4)		ZCG for Column B (mm)	
Battery 1	-44.68	0	1.116	716.5186488	0		-1.363438774	Below Center
Battery 2	-44.68	0	1.116	716.5186488	0			
Thruster 1	112.93	112.93	0.427	571.9837722	571.9837722		ZCG for Column C (mm)	
Thruster 2	-163.246	-163.246	0.427	454.0566202	454.0566202		9.395624771	Above Center
Thruster 3	-163.246	-163.246	0.427	454.0566202	454.0566202			
Tube	0	0	0.138	0	0			
End Cap 1	0	0	0.393	0	0			
End Cap 2	0	0	0.393	0	0			
O Ring 1	0	0	0.238	0	0			
O Ring 2	0	0	0.238	0	0			
Internal Rail (x2)	0	0	0.067	0	0			
Electrical Tray	0	0	0.311	0	0			
Electrical Compo	0	0	0.567	0	0			
Antenna Casing	243.23	243.23	0.34	3907.6982	3907.6982			
T Rail 1 (Antenna	116.42	116.42	0.821	928.9141533	928.9141533			
T Rail 2 (Foam)	0	0	0.821	0	0			
T Rail 2 (Foam)	0	0	0.821	0	0			
Foam	0	0	0.608	0	0			
Sum			9.269	7749.746663	6316.709366			
Note: Moment of Inertia with Batteries Lower is larger								

Figure 3: Z center of gravity calculation.

Appendix E: Matlab Servo and Buoyancy Calculations

Matlab Script to solve amount of buoyancy foam needed to Flip and stay Horizontal

Listing 4: MATLAB code for GPS waypoint bearing calculation.

```
clc;
clear;

% --- 1. DESIGN REQUIREMENTS & CONSTANTS ---
rho_water = 1025;    % Density of saltwater (kg/m^3)
rho_foam  = 192;     % Density of buoyancy foam (kg/m^3)
g = 9.81;            % Gravity (m/s^2)

% --- 2. PROFILER PROPERTIES (FIXED BODY) ---
V_p = 0.033981464453;            % Volume of profiler hull (m^3)
m_p = 20.4;                      % Mass of profiler (kg)
x1 = 0.4572;                     % Distance of center of bouyacy of tube to
                                 % refernce point
x2 = 0.6858;                   % Center of Mass / LCG of the profiler (m)
x3 = x2;                       % Rn they are the same distacance

Fg = m_p*g*x2;
Ft = rho_water*g*V_p

a = 2*m_p*x2;
b = rho_water*V_p*x1;
c = x3*rho_foam;

V_foam = ( a - b ) / c;

fprintf(" Volume of foam needed to not cause a not
rotational torque: %.6f mm^3 \n",V_foam*1e9)

% Calculate required length of foam block (assuming it's a cylinder)
d_buoyancy = 0.16;    % Diameter of foam block (m)
```

```
A_foam = (pi * (d_buoyancy/2)^2); % Cross-sectional area of foam
Length_foam = ( V_foam/2 ) / A_foam;

fprintf("Length of boyancy foam needed: %.6f mm\n", Length_foam);

% Lead Screw Characteristics (ACME 3/8'')
D = 0.0127; % Major diameter
P = 0.00254; % Pitch (m)
a = 14.5; % thread wall angle in degrees
d_p = 0.01143; % pitch diameter in m

% Net Buoyancy (The force pushing BACK against your system)
F_load = V_foam*rho_foam*g;

% Calculating Torque
f = 0.2; % coefficient of friction
d_c = 2*D; % collar diameter
f_c = 0.15; % collar coefficient of friction

T_c = f_c * F_load * (d_c/2);
T_push = ((F_load * d_p)/2) * (((f * pi * d_p) + P * cosd(a)) / ...
         ((pi * d_p * cosd(a)) - (f * P))) + T_c;

% --- BACKDRIVE CHECK ---
% Lead angle (lambda) is the angle of the threads
lambda = atand(P / (pi * d_p));

% Torque required to LOWER the load (if this is negative, it will backdrive)
T_lower = ((F_load * d_p)/2) * (((f * pi * d_p * cosd(a)) - (P)) / ...
          ((pi * d_p * cosd(a)) + (f * P))) + T_c;

fprintf('Torque needed to move load: %.6f N*m\n', T_push);

if T_lower > 0
    fprintf('STATUS: The system is SELF-LOCKING. No backdrive will occur.\n');
else
    fprintf('STATUS: WARNING! The system may BACKDRIVE.
    External force exceeds friction.\n');
end

% Thrust Generated (Efficiency-based)
n = 0.2;
Fa = (2*pi*n*T_push) / P; % Fixed formula from 1*pi to 2*pi
fprintf('Thrust Generated: %.2f N\n', Fa);
```