

SMART ANCHORLESS MARKER BUOY

ECE 481W Proposal

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ABSTRACT

This document outlines a proposal that includes the design, analysis, and integration of a Smart Anchorless Marker Buoy (SAMB) system using thruster-based station-keeping without the need for a traditional mooring. A low-power global navigation satellite system (GNSS) positioning, LoRa-class long-range telemetry, and dual electric thrusters under embedded control (Raspberry Pi 3 + ESP32) are combined in this system. The buoy is designed to operate in harbor conditions with a maximum of 5 knots wind and 0.3 m/s surface current while maintaining a position error of 1.5 to 2.5 m RMS and 24-hour endurance by means of a 12 V 100 Ah battery and two 20-W solar panels. The resulting integrated prototype, modular firmware stack, controller calibrated on a simplified hydrodynamic model with field calibration, and cost-constrained bill of materials amounting to \$1,952 (exclusively for optional elbows) are listed as deliverables. The project is predicted to have a positive impact on the environment by providing a safer temporary navigation marking, quicker incident response, and allowing for the coastal research deployments to be more flexible.

ACKNOWLEDGEMENTS

The project will receive funding from Old Dominion University's ECE department, the project advisor as well as the Universities Dean's office. The group expresses gratitude towards the department for the given accessibility to finances and industry technology, and towards the project supervisor, Dr. W. Steven Gray, for his oversight.

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I. INTRODUCTION

Buoys have an extensive history of use in research fields dating as far back as 1967. The National Data Buoy Development Project (NDBDP) created the first extensive network of buoys that acquired large swaths of environmental data alongside specialized buoys that served more specific needs [1]. These buoys are able to acquire important data such as meteorological, subsurface temperature, and wave spectra data, which to this day contribute to important research organizations such as the NOAA, who control the National Weather Service in the United States [1]. In present, buoys contribute to a diverse set of marine industries, including navigation, military, and fishing. Considering the versatility of buoys and the potential engineering problems that designing one encounters, such as signal processing and large-distance communication, the group decided to work on designing a “Smart Anchorless Buoy System” for both the education and experiencing the engineering design process.

The term “buoy” covers a wide range of floating bodies that do not necessarily include technology. Based on the functionality needed, there are many different existing types of buoys. These include lateral and non-lateral buoys, where the former are used for navigation and the latter are used for every other use case [2] [3]. Under the lateral category, there are port and starboard-side marker buoys, bifurcation and junction buoys, and lighted buoys or daymarks, which all are used to guide sea vehicles. Non-lateral types include fairway markers that mark safe waters, danger markers, control buoys that impose restrictions, and research buoys that measure oceanic conditions [2] [3]. This project focuses on designing a general-use marker buoy that could be used for both lateral and non-lateral purposes.

I.1. DESIGN PROBLEM

Come up with a concept, do the constructions, and carry out testing of a self-sufficient surface buoy which can keep its position without a mooring in mild harbor conditions. The buoy will be required to: (i) keep its position within a very small limit by means of thrusters; (ii) work for 24 hours on battery plus solar recharge; (iii) send telemetry (position/health) to the shore through a long-range communication system; and (iv) satisfy cost, safety and field-service limitations.

I.2. DESIGN FUNCTION

The proposed buoy will autonomously maintain its position using an onboard control system that processes GPS data and activates small submersible motors, or thrusters, to counteract drift from currents and wind. A solar-powered battery system will supply continuous energy to the computing, navigation, and propulsion subsystems. A bright blinking light will serve as a visual marker, and a wireless module will transmit GPS coordinates to a receiver on shore or on a vessel. All components will be enclosed within a waterproof housing mounted on a buoyant structure that ensures stability and visibility in open water. These functions can be divided up into subsystems. The interactions between the subsystems are shown in Figure 1.

- **Sense:** GNSS (position/velocity), IMU (attitude/accel), current/voltage sensors.
- **Decide:** Embedded control (Raspberry Pi 3 supervisory; ESP32 real-time loops).
- **Actuate:** Dual underwater thrusters via ESCs for surge/sway control.
- **Communicate:** LoRa-class link for periodic beacons and alerts; local LED beacon for visibility.
- **Power:** 12 V Li-ion battery, in-line fusing, DC-DC regulation, solar charging.

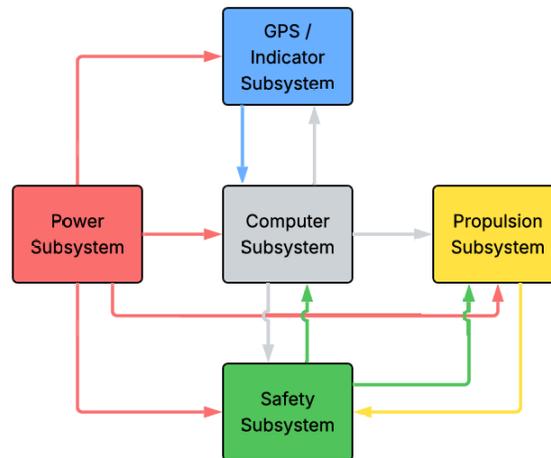


Figure 1 - Simplified diagram of functional relationships in system.

I.3 QUANTITATIVE OBJECTIVES

The prototype will aim to achieve the following measurable goals:

- Maintain its GPS position within ± 2 meters in calm to moderate marine conditions.
- Operate continuously for at least 14 days using solar charging and onboard batteries.
- Transmit GPS coordinates wirelessly every 30 seconds.
- Emit a light signal visible from 500 meters at night.
- Withstanding rain, salt spray, and brief submersion without loss of function.

II. DESIGN PROCESS

The group proceeded through the first steps of the engineering design process to compose a workable design that successfully falls within all the constraints that come from current engineering standards, ethical guidelines, and the overall design goals. First, the major

constraints are outlined, then design choices are analyzed together until a good balance of design choices is reached.

II.1 DESIGN CONSTRAINTS

The biggest constraint on this project is time, as the group is given two semesters to design and build the project. The time constraint impacts the buoy's safety system the most. For example, the bright colors most buoys are painted with for the purpose of visibility won't be implemented for this project. Furthermore, the design can't be too specialized, since the design is meant for general use. Different buoy types have different colors, so it's more apt to leave the outside unpainted. Another omitted safety feature could've been a self-righting system where the buoy could reorient if rough conditions cause the buoy to tip over.

The second biggest design constraint is finances, which mainly impacts the structural materials of the buoy. The buoy must be made out of a marine-grade material to avoid corrosion from salt water. Stainless steel is a common material, but manufacturing metal is well-outside the group's budget and abilities. Thus, the current design had to use PVC materials, which unfortunately forces an environmental trade-off by putting more plastic in waters.

II.2 ALTERNATIVE DESIGNS

The following table summarizes the broad categories where the group had to choose what to implement in the design.

Table 1 - Design choices for different function of the SAMB.

Category	Design Choices
Power Source	Combustion, solar , wind, or hydropower
Battery	Lead-acid, Li-ion, or LiFePO₄

Wireless Communication	Bluetooth, Wi-Fi, Cellular/LTE, or Radio
Error Control	Proportional or PID
Computer	Arduino or Raspberry Pi
Microcontroller	ESP32
Structural Material	Stainless steel, PVC , polyethylene foam
Measurement Devices	Accelerometer , barometer, thermometer

II.3 CURRENT DESIGN

Taking from Table 1, the group moved forward with the following design choices, with reasons given for each:

- **Power Source:** It's preferred to have an environmental-friendly and thus renewable energy source. A wind turbine would be too unstable for a floating body, and calm water conditions make hydropower unviable. Therefore, the system obtains power through solar panels.
- **Battery:** The buoy should require as little maintenance as possible, therefore being long-lasting in addition to being environmentally friendly. Lead-acid batteries are heavy, have short life cycles, and are prone to leakage [4]. Lithium-iron-phosphate batteries are more expensive in the short term but have much longer lifespans and are relatively safe. Considering the battery will be in a closed container on top of water, the current design uses a LiFePO_4 battery for safety, despite the increased cost.
- **Wireless Communication:** Bluetooth, LTE, and Wi-Fi are all considered WPAN technologies, so they all have very short ranges. The buoy needs to be remotely controlled across large distances, so the only possible method of communication is radio.

The buoy uses the public-use LoRa protocol to facilitate communication between the user and the buoy.

- **Error Control:** The buoy corrects its position via an error signal between its current position and the desired position. This error can be fed forward using a proportional or proportional-integrator-derivative controller. Proportional controllers are simpler, but PID controllers can be finer tuned and have zero steady-state error.
- **Computer:** The buoy's central processor needs to be powerful enough to output power to other subsystems and run real-time parsing of location data. Arduinos are versatile and cheap, but do not have the necessary power for the motor controller. A Raspberry Pi 3 is therefore chosen for its physical size, processing speed, and power output.
- **Microcontroller:** An additional microcontroller sits between the computer and propellers for quicker and more accurate positional control. The microcontroller needs to be fast enough to do real-time error correction and powerful enough to drive the propellers. A microcontroller with an ESP32 is therefore chosen.

III. PROJECT MANAGEMENT

III.1. DISTRIBUTION OF WORK

Viewing the project through the subsystems-model shown in Figure 1, the project's tasks were distributed based on the subsystem category:

Table 2 - Distribution of project tasks among team members.

Team Member	Role
RJ Bailey	Project lead, power subsystem, compute subsystem
Taha Bilal	GPS/Communications subsystem, user interface
Brandon Stuck	Beacon subsystem, junction box layout
James Ward	Propulsion subsystem, safety subsystem and general safety

III.2 DELIVARABLES

Table 3 - Weekly timeline of project goals.

Weeks	Goals
1-3	Finalize prototype design, obtain components
3-7	Testing characteristics of all components, reorder if necessary
7-11	Develop body (CAD) and circuit (MATLAB) simulations, draft user interface, obtain and parse GNSS signals
11-15	Evaluation of system, reiterate design if necessary
15-16	Present working prototype

III.3 BUDGET SUMMARY

A detailed breakdown of subsystem costs can be found in Appendix A. The total estimated cost to build the SAMB prototype is \$1,952.00. This estimate includes all major hardware components across the Power, Computer, Movement, GPS, Beacon, and Structural subsystems, in addition to a \$350 allowance for unforeseen expenses.

By contrast, the total confirmed funding for the project is \$1,250 derived from:

- **ODU Dean's Office:** \$650
- **ECE Department Funding:** \$300
- **Advisor Contribution:** \$300

This provides a funding shortfall of about \$702, as the full cost of the prototype exceeds the resources available. In addressing this deficit with the view to staying within the funded amount, several cost-saving measures will be implemented by the team:

1. Utilize Used, Spare, or Donated Components

Where safe and appropriate, the team will source used or previously owned parts, including:

- PVC framing sections
- Wiring and connectors
- Spare sensors, prototyping boards, and small electronics
- Thruster mounting hardware

Team members will also contribute extra components they already own, reducing the need for new purchases.

2. Seek Additional Donations or Funding Opportunities

To further close the budget gap, the team will explore:

- Possible donations of hardware from ODU laboratories
- Support from faculty with surplus materials
- Additional internal or external mini-grants
- Industry or vendor donation programs (e.g., discounted thrusters, PVC, sensors)

3. Substitute Lower-Cost Part Options

Where possible without compromising functionality, the team will:

- Compare vendors for cheaper equivalents
- Consider refurbished or open-box items
- Evaluate structural design adjustments to reduce material usage

While the total estimated cost of \$1,952 is higher than the available money of \$1,250 by \$702, the team plans to cover this difference by using a combination of used or spare parts, looking for more donation or funding sources, and selecting inexpensive parts. The sum of these actions will be a guarantee that the prototype will be finished without exceeding the budget.

IV. DESIGN DETAILS

IV.1 RELEVANT STANDARDS

The “Smart Anchorless Buoy” (SAMB) project has several devices that utilize wireless communication. Using radio signals for wireless communication requires understanding the radio-spectrum standards set by the FCC guidelines. Without considering FCC and IEEE, standards, the buoy could pose a physical hazard in multiple ways.

The IEEE family of standards for wireless communications is IEEE 802. They are separated based on the range needed, speed of the network, and number of endpoints (e.g. LAN vs WAN). The interface to control the buoy does not necessarily have to be fast, so a low-rate channel for communication covering a wide area is more than appropriate. Since the channel is only going to have two endpoints (the buoy and the user), the channel could be classified as a mix between a wireless personal-area network (WPAN) and a wide-area network (WAN). It’s not exactly a WPAN because of the large range needed, nor a typical WAN because of the small number of devices involved. To specify, the buoy needs to consider standard IEEE 802.15.4, “Low-rate wireless networks”, which outlines parameters for broadcasting signals on a low-rate wireless personal-area network (LR-WPAN) [5].

IEEE 802.15.4 defines an LR-WPAN device as consisting of sublayers which are structured from the bottom-up as follows: physical (PHY), medium access control (MAC), and other higher-level layers [5]. The antenna and signal modulator fall into PHY, the layer that this standard is mainly concerned with. These two devices would determine the characteristics of the physical signal and should be chosen to fit the standard.

The standard requires broadcast signals to be 915 MHz for LR-WPANs, with a power up to 20 dBm [5]. However, IEEE 802.15.4 cannot be completely implemented into the system, because it needs to communicate its position across large distances. The only way this is possible is to use radio-frequency signals. However, due to restrictions placed by the FCC for radio communications, and due to the low power and frequency limit laid out in IEEE 802.15.4, another standard must be used to transmit the buoy's location. The solution is to go through a different standard that allows private use, such as cellular, Wi-Fi, or the LoRa protocol. While LoRa operates in a similar low-rate, long-range domain as IEEE 802.15.4, it is not an IEEE standard. Instead, it uses different modulation techniques and protocols, designed to extend the viable range while remaining within unlicensed RF bands [6].

IV.2 ETHICS

The project must consider engineering ethical guidelines, specifically the IEEE Code of Ethics (CoE). Considering the ethical guidelines means the project will have some necessary constraints. This section overviews the possible impacts of these constraints on team members and the overall design of the project.

First, the team members must reflect proper collaboration and responsibility. IEEE CoE clause I.5 emphasizes the importance of seeking and offering honest criticism. Instead of

working in isolation, this means team members should review each other's designs, call out mistakes, and ensure feedback is addressed. Safety is one example of responsibility given to team members, as stated by IEEE CoE clause I.6 which requires that members be qualified by training or experience. This means doing lab safety training provided by EHS, and any additional safety trainings for certain lab processes. Moreover, IEEE CoE clause I.2 states to share all gained knowledge of the technologies used for the buoy. This would come in the form of presentations and proposals. It also requires that every team member be knowledgeable enough to present their findings. Ethical team conduct would strengthen the rigor of the project, encourage teamwork, and even out workload distribution.

Second, the design itself is constrained by the CoE. IEEE CoE clause I.1 requires "hold[ing] paramount the safety, health, and welfare of the public." A buoy can be a public hazard in a few ways. Having propellers poses hazards to marine life, so the final design would need protective coverings on propellers. The buoy's power source should be a clean, zero-carbon source, hence using solar panels and limiting energy consumption. Furthermore, IEEE CoE clause II.9 stresses avoiding harm to others' property or reputation. This requires ensuring the buoy does not interfere with other vessels or marine research equipment, so a periodic pulsing light and radar ping would be implemented.

IV.3 OVERVIEW OF SUBSYSTEMS

Autonomous Anchorless Marker Buoy Wiring diagram

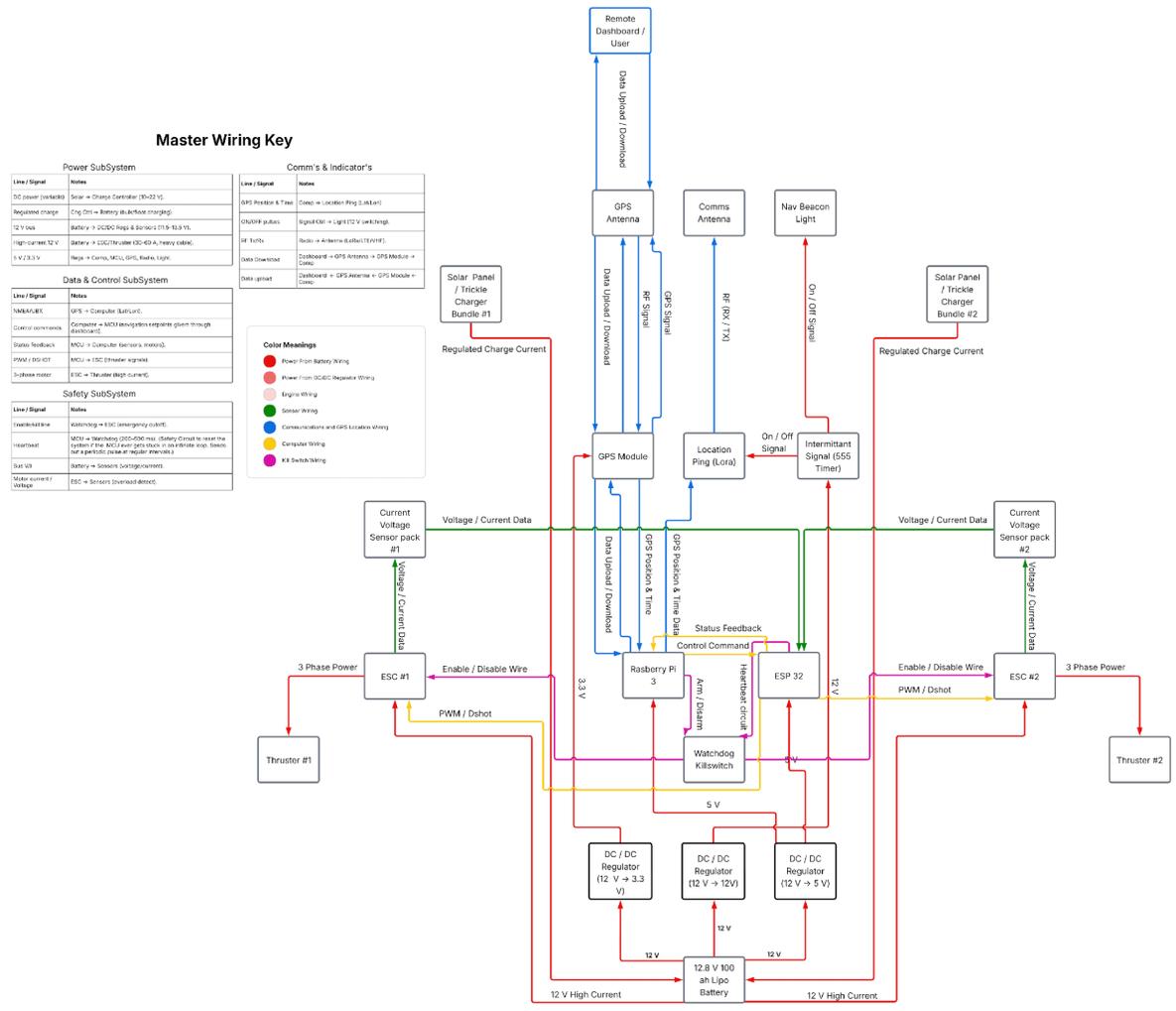


Figure 2 - Full block diagram of entire buoy system.

This section describes the specific components used for each subsystem and how they fit within the constraints given by the standards and ethics outlined in earlier sections. The full itemized list of components can be found in Appendix A.

Power Subsystem

- Components: 12 V 100 Ah LiFePO₄ battery, two 20 W solar panels, inline fuses, voltage/current sensors.
- Solar panels and LiFePO₄ cells satisfy renewable-energy and electrical safety expectations. Components operate below 20 V DC, within IEEE safety voltage limits [5].

Movement (Propulsion) Subsystem

- Components: Two marine-grade brushless thrusters with dual ESC controllers.
- Electrical components conform to IEEE 802.15.4 PHY power restrictions (< 20 dBm emissions) [5]. Brushless motors operate within marine equipment norms for underwater devices. Protective covers reduce danger to marine-life, taking into account ethical environmental safety.

GPS / Communication Subsystem

- Components: Heltec WiFi LoRa 32 module, SparkFun GPS Breakout (Neo-M9N), Proxicast GPS antenna, SMA-to-U.FL cable.
- Follows IEEE 802.15.4 LR-WPAN principles for low-rate communication; extended via 1.1 LoRaWAN protocol. LoRa operates in unlicensed 915 MHz ISM band, consistent with FCC Part 15 and IEEE's low-power broadcast requirements [5].

Computer / Control Subsystem

- Components: Raspberry Pi 3 Model B, ESP32 microcontroller, protoboard, wiring
- Runs PID control for propulsion per IEEE control-system modeling best practices; ESP32 chosen for efficient real-time control under IEEE 1471-style architectural separation.

Beacon / Safety Subsystem

- Components: Marine-grade navigation light, waterproof junction box, radar/visual signaling provisions.
- Meets IEEE CoE I.1 and II.9 (safety and non-interference with public vessels) [5]. Visual signaling aligns with U.S. Coast Guard and maritime visibility guidelines; waterproof enclosure ensures electrical isolation per IP66.

Structural

- Components: PVC pipe structure, couplers, bulkhead connectors, clamps, rubber sealants.
- PVC provides buoyancy and electrical insulation, minimizing corrosion and adhering to environmental sustainability.

V. PRELIMINARY ANALYSIS

Station-Keeping Model: For controller prototyping, a point-mass subjected to linear drag is considered in a plane. The controller applies PID with anti-windup in combination with a thrust allocator for the distribution of net commands to both ESCs. Initial setpoints are aimed to achieve ≤ 2.5 m RMS error for minor disturbances.

Energy & Endurance: The battery pack capable of supplying the power of 12 V 100 Ah (~1.2 kWh) keeps the avionics plus beacon running for more than 24 h under the condition of

minimum thruster operation. The duty cycle restrictions and deadbanding keep the average thruster draw low; the solar panels give a trickle recharge during daytime.

Telemetry: The use of LoRa payloads (typically ≤ 12 bytes) every 30–60 s with a low spreading factor is likely to result in a multi-kilometer range in line of sight with a well-placed gateway.

VI. BROADER IMPACTS

VI.1. SOCIETAL, ENVIRONMENTAL, AND ECONOMIC IMPACTS

The Smart Anchorless Marker Buoy has a wide range of uses across many maritime industries. Buoys are most often used for the navigational safety of ships. They can work as both a hazard marker and a navigational path marker. Marker buoys help ships avoid physical hazards like shallow waters or sandbars. Buoys can also help guide ships on optimized shipping routes. This could be helpful, as an example, for ships who have lost GPS communication and need to manually steer. Although not in current plans, the buoys can have additional measurement devices to help obtain general oceanic data for global databases, aiding scientific research [7]. It can also aid with early tsunami and earthquake warnings.

The buoy brings a few economic benefits to marine industries. As mentioned before, improving the navigational safety ships naturally saves companies enormous amounts of money. Reducing collisions would save on repair and injury costs. Being a “smart” buoy also saves money in the long-term over “standard” buoys. It costs time to deploy and retrieve buoys, so having one remote-controlled eliminates the labor cost of moving around. Having an array of smart buoys may also prove cost-effective. Users would be able to move buoys en masse and

could edit marked paths in real-time. This could be used for improvised detours in case of a sudden large blockage.

There is also the environmental impact of the buoy system, both on marine life and the physical environment itself. Buoys can mark bodies of water dense with marine life so that ships can avoid accidentally traversing and destroying massive fish populations. Furthermore, by self-correcting with propellers instead of an anchor, the buoy removes a physical obstacle for fish populations. Since the buoy is solar-powered, there is no concern for producing any waste. Having a renewable energy source means no carbon emissions nor dumping used fuel in water. If given additional instruments, the buoy can help aid in monitoring the general health of the ocean. Things like salinity, pollution, and temperature can be kept in check and be provided as data for climate change models.

The smart buoy has direct societal impact by improving industries and informing public-deliberation for local marine laws. Even without measurement devices, analyzing the movement of buoys can provide helpful data. Coastal communities, which depend on the fishing industry, benefit from improved fish population management informed by buoy data. Shipping industries benefit from better forecasts of waves and currents. If given instruments, a lot more can be achieved. Systems could monitor the movement of pollutants into fresh bodies of water, or the motion of large fish populations. Having more public data in general helps inform policy-making, which in turn could improve regulations for coastal areas.

VI.3. LIFELONG LEARNING

Working on this project has potential to bring several educational benefits for the group. The group interacts with several industries through this project: signal processing, mechanical

design, electronics, water-tight systems, etc. The project helps broaden the team’s skillset in these industries and additionally in team-collaboration. The design process models how professional engineers create, iterate, test, and present new products. The team also learns how to balance costs with quality. Researching also familiarizes the team with current industry standards and how to navigate ethical guidelines. The project also encourages creative thinking and problem solving.

VII. APPENDICES

APPENDIX A. BILL OF ITEMS

Table 4 - Itemized budget, separated by subsystem.

Power Subsystem:	
Battery	\$129.99
Solar Panel kit x2	\$119.98
DC to DC voltage regulators	\$13.99
Inline fuses	\$12.99
Current & voltage sensors x2	\$17.98
Computer Subsystem:	
Raspberry Pi 3	\$35.00
ESP32	\$10.00
IMU Module	\$10.99
555 timing chip	\$0.50
Wiring	\$27.99
Protoboard	\$17.99
Wiring components	\$20.96
	\$123.43
Movement Subsystem:	
Thrusters x2	\$85.96
ESC for motor control x2	\$120.00
GPS Subsystem:	
Heltec WiFi LoRa 32	\$26.97
Proxicast Active/Passive GPS Antenna SMA	\$45.95

SparkFun GPS Breakout	\$70.95
SMA to U.FL Cable - 150mm	\$2.75
Beacon Subsystem:	
Light	\$18.00
2 pin bulkhead connector	\$15.99

Structural / Extra:	
Waterproof Electrical Junction Box	\$37.96
PVC (10 inch pipe, 10->6 reducer, 6 in cap, 4 inch tees, 4inch pipe, 4in caps, flat stock, hardware for clamp, rubber tape) & Fittings / Couplers	\$650.00
3 phase wire bulkhead connectors	\$10.99
Waterproof Passthrough Connectors	\$23.98
PVC Pipe cement (watertight)	\$21.29
Expanding foam	\$52.99
Possible elbow connectors	\$797.21
Unknown costs that may arise	\$350.00
Estimated Price Per Unit:	\$1,952.00
Financial Support:	
ODU Dean's office:	\$650
Electrical and Computer Engineering Department Funding:	\$300
Advisor Contribution:	\$300
Total Funding Budget:	\$1250

APPENDIX B. PROPOSAL CONTRIBUTIONS

Bailey:

- Finalized decisions
- Design problem and function
- Block diagrams
- Alternative designs
- Preliminary analysis
- Itemized bill
- Research on components

Ward:

- Design problem
- Quantitative objectives
- Research on components

Bilal:

- Introduction
- Design process
- GPS and LoRa research
- Ethics and standards
- Research on components

Stuck:

- Research on components
- Block diagrams
- GPS research and code

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