SMART ANCHORLESS MARKER BUOY

ECE 482 Final Report

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ABSTRACT

The purpose of this project was to develop a new type of marker buoy that can hold its position on the water without using a traditional anchor. Standard buoys rely on heavy chains and weights, which makes them costly and difficult to deploy, relocate, or retrieve. The new design replaces the anchor with electric thrusters and GPS guidance, allowing the buoy to adjust its position automatically whenever it drifts due to wind or water currents.

The prototype buoy is powered by a long-lasting battery that is recharged by solar panels, enabling it to operate for a couple of weeks with little to no maintenance. It also includes a bright blinking light for visibility and a wireless system that sends its GPS location to a computer every five to ten seconds.

This prototype integrates multiple subsystems, including power, computer control, GPS navigation, wireless communication, lighting, propulsion, safety mechanisms, and the structural frame. The design objective was to build a working prototype that can stay within three meters of its target position, function reliably in normal environmental conditions, and ensure safe long-term operation.

ACKNOWLEDGEMENTS

This project received funding from Old Dominion University's Electrical and Computer Engineering (ECE) department, the Batten College of Engineering and Technology's Dean's office, and the project's advisor, Dr. W. Steven Gray. The group expresses gratitude towards the ECE department for the given accessibility to finances and industry technology. We would also like to thank the student members of IEEE and the members of M-Lab for their help. Additionally, we would like to further thank Dr. W. Steven Gray for his oversight and guidance.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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]. At present, buoys contribute to a diverse set of marine industries, including navigation, military, and fishing. Considering the versatility of buoys as markers and research vessels, along with their impact on marine ecosystems, the general goal of this project is to develop a new type of “Smart Anchorless Buoy System” .

The term “buoy” covers a wide range of floating bodies that do not necessarily include technology. Based on the functionality needed, there are numerous types of buoys that fall in two categories: lateral and non-lateral buoys. Lateral buoys are used to assist in navigation, while non-lateral buoys 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 that mark obstacles, control buoys that impose restrictions on travel, 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

The given design problem was to design a miniaturized anchorless marker buoy with the ability to self-correct its position to a set of GPS coordinates, while under moderate harbor or shore conditions. The buoy had to remain at its designated position by correcting any drift that may result from wind, currents, or any other environmental disturbance.

Apart from being able to control the position of the buoy, there were additional design requirements for it to fulfill. First, it had to run on a battery powered by solar energy, and second, it had to transmit health and positional information about itself to the user through the remote communication network. Finally, the implementation had to be feasible in the limited time period available.

I.2. DESIGN FUNCTION

The smart anchorless marker buoy (SAMB) was intended to function as an autonomous floating marker capable of sensing its current position, determining deviation from a target position, and applying corrective motion through electrically driven underwater thrusters. A GPS module supplied real-time location information, while onboard processing hardware evaluated that information and issued control commands. A wireless communication subsystem provided periodic telemetry updates to a remote user interface. A solar-supported battery subsystem powered the electronics and propulsion hardware, and a blinking navigation light improved the buoy’s visibility for safety. Figure 1 below shows the relationships between the following subsystems:

- **GPS / Indicator**: GNSS (position/velocity), IMU (attitude/accel), current/voltage sensors. LoRa-class link for periodic beacons and alerts.
- **Computer**: Embedded control (Raspberry Pi 3 supervisory; ESP32 real-time loops).
- **Actuate**: Dual underwater thrusters with ESC interface.
- **Power**: 12 V Li-ion battery, in-line fusing, DC-DC regulation, solar charging.

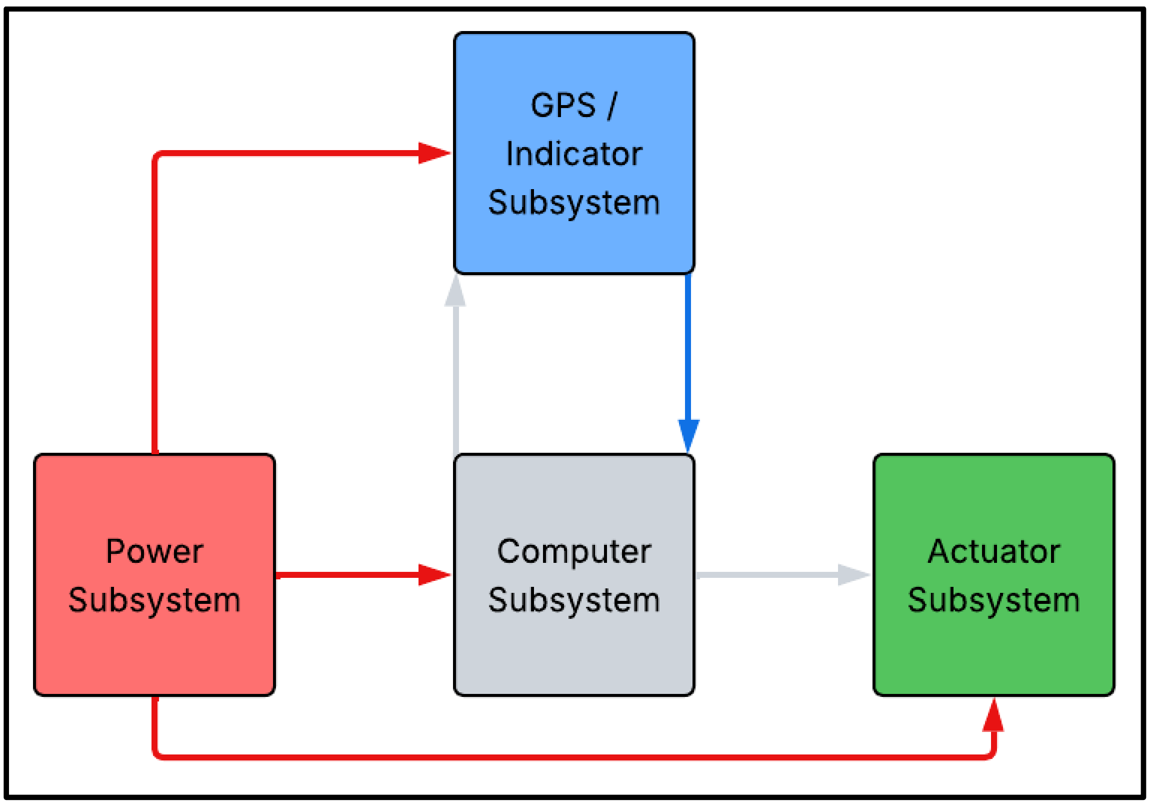


Figure 1. Simplified diagram of functional relationships in the system.

I.3 QUANTITATIVE OBJECTIVES

At the start of the project, the team defined multiple measurable performance objectives to guide the design. These objectives were used as points of reference for prototype evaluation and testing:

- Maintain position within ±3 meters under mild environmental conditions
- Operate continuously for a minimum of 14 days using solar-assisted power
- Transmit GPS and system data every 5–10 seconds
- Sustain signal communication at distances up to 500 meters
- Resist environmental exposure including rain, salt spray, and partial submersion
- Generate sufficient thrust to counteract drift velocities up to approximately 0.5 m/s

II. DESIGN PROCESS

The engineering design process was systematically executed while designing the SAMB system. This engineering design process involved identifying problems, determining requirements, and formulating concepts, followed by analyzing subsystems and finalizing through multiple iterations.

The suitability of initial concepts was determined based on factors such as feasibility, cost, and performance. Several alternate solutions were examined for each subsystem, involving different options related to the source of power, modes of communication, control mechanisms, and choice of materials. The design was subsequently optimized using simulation and tests.

Components and subsystems were designed separately before being assembled together as a system.

II.1 DESIGN CONSTRAINTS

The biggest constraint on this project was time, as the group was given two semesters to design and build the project. The time constraint impacts the buoy's non-core safety subsystem the most. For example, the bright colors of which most buoys are painted with for the purpose of visibility were not implemented for this project. Regardless, since the design needed to avoid being too specialized for the sake of general use, the design being left unpainted was more apt for allowing different colors for different buoy types. Another omitted safety feature was an additional self-righting system for pitch and roll, where the buoy could reorient if unexpected rough conditions cause the buoy to tip over. The time constraint also forced the testing for operational life to be cut, since it was unfeasible to test for power use over multiple days within the few weeks allotted.

The second biggest design constraint was finances, which mainly impacted the structural materials of the buoy. The buoy should have been made out of a marine-grade material to avoid corrosion from salt water. Although stainless steel is a common material, 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

A number of alternative designs were considered during the design process. This included a hybrid solution that used both an anchor and propulsion but was ruled out since it would not satisfy the main requirement of doing away with anchoring equipment.

Alternative energy sources considered include wind and hydropower. Wind power creates instabilities on a floating platform, and hydropower cannot be generated in areas with slow-moving currents. Therefore we opted for solar energy since it is renewable and consistent. Possible methods for transmitting data include Wi-Fi, Bluetooth, and cellular networks. All of these were rejected on the grounds of their short range or excessive power requirements. LoRa was selected because it is rangeable and requires little power. Proportional control and PID controllers were considered for use in control processes. The PID controller was selected because it reduces steady state error and makes systems stable. Table 1 below highlights the broad classes in which the group chose what to incorporate into the design.

Table 1. Design choices for different functions of the SAMB.

Category	**Design Options**	**Final Choices**
Power Source	Combustion, solar, wind, or hydropower	Solar
Battery	Lead-acid, Li-ion, or $LiFePO_4$	$LiFePO_4$
Wireless Communication	Bluetooth, Wi-Fi, Cellular/LTE, or Radio	LoRa Radio
Error Control	Proportional or PID	PID
Computer	Arduino or Raspberry Pi	Rasberry Pi
Microcontroller	ESP32	ESP 32
Structural Material	Stainless steel, PVC, polyethylene foam	PVC
Measurement Devices	Accelerometer, barometer, thermometer	Accelerometer

II.3 FINAL DESIGN

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

- **Power Source**: It is 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 final 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. For this reason, PID controllers were used in the prototype.

- **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 was 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 was 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 as shown in table 2:

Table 2. Distribution of project tasks among team members.

Team Member	Role
RJ Bailey	Project lead, power subsystem, propulsion subsystem
Taha Bilal	GPS/Communications subsystem, user interface
Brandon Stuck	Beacon subsystem, junction box layout
James Ward	Computer subsystem

III.2 PROJECT TIMELINE

Tables 3 and 4 showcase the project timeline separated by semester. The first semester consisted of research and proposals. The second semester consisted of building and testing. Both tables follow the same color format, where green represents planned durations and blue represents actual durations.

Table 3. Timeline for research and assignment's

SMART ANCHORLESS MARKER BUOY											
Group Members: RJ Bailey, James Ward, Taha Bilal, Brandon Stuck, William Benett											
Advisor: Dr. W. Steven Gray											
Legend:	Planned Duration	Actual Duration	Section Title								
Project Start Date: 8/26/2025											
Project End Date: 5/10/2026											
Activity Number	**Activity Name**	**August**	**September**	**October**	**November**	**December**	**January**	**February**	**March**	**April**	**May**
1	RESEARCH AND DESIGN										
1.1	System Requirements Definition										
1.2	Subsystem Concept Design										
1.3	Design Simulation and Modeling										
1.4	Power System Design										
2	CLASS ASSIGNMENTS										
2.1	Ethics Paper										
2.2	Standards Paper										
2.3	Midterm Proposal Paper										
2.4	Midterm Presentation										
2.5	Midterm Report										
2.6	Final Proposal Paper										
2.7	Final Presentation										
2.8	Final Report										

Table 4. Timeline for requisition, building and testing.

SMART ANCHORLESS MARKER BUOY

Group Members: RJ Bailey, James Ward, Taha Bilal, Brandon Stuck, William Benett
Advisor: Dr. W. Steven Gray
Legend: Planned Duration | Actual Duratio | Section Title
Project Start Date: 8/26/2025
Project End Date: 5/10/2026

Activity Number	Activity Name	August	September	October	November	December	January	February	March	April	May
3	Ordering and Requisition										
3.1	Submit Component Orders										
3.2	Receive and Inspect Materials										
4	FABRICATION										
4.1	Power Subsystem Assembly										
4.2	Computer & Control System Assembly										
4.3	Thruster and Safety System Assembly										
4.4	Full System Integration										
5	TESTING AND VALIDATION										
5.1	Prototype Dry Testing										
5.2	Field Testing and Data Collection										
5.3	System Validation & Final Adjustments										

III.2 DELIVERABLES

Table 5 shows the goals of each phase of the project during building and testing. Due to shipment delays and weather conditions, testing was delayed and possible further iterations were unable to be developed. Beyond that, most deliverables were met on time with the sole exception of the evaluation of the system.

Table 5. 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

IV. DESIGN DETAILS

IV.1 RELEVANT STANDARDS

The 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 is 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 training 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

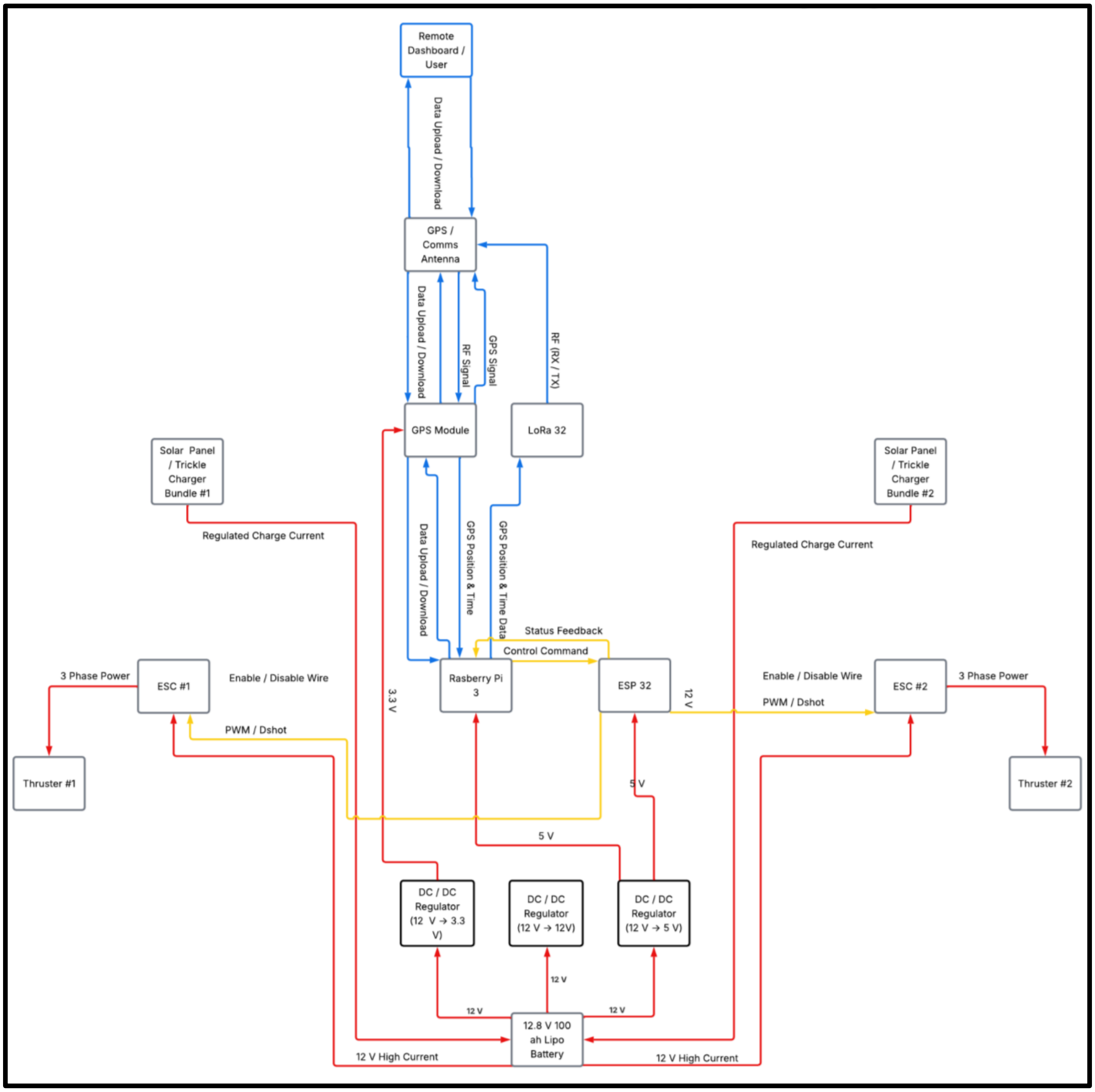


Figure 2. Full block diagram of the entire buoy system.

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 $LiFePO_4$ battery, two 20 W solar panels, inline fuses, voltage/current sensors.
- Solar panels and $LiFePO_4$ cells satisfy renewable-energy and electrical safety expectations. Components operate below 20 V DC, within IEEE safety voltage limits [5].

Movement (actuator) 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.
- Utilizes The Things Network's (TTN's) service to send coordinates to the TTN webpage console. The Heltec LoRa board automatically parses the Neo-M9N's location data, of which the code can be found in Appendix B. LoRaWAN 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.

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

Part of the design process includes initial testing of the conceptual model through written analysis and computer simulations. This allows for early detection of potential problems with the function of individual subsystems, and provides early control models to determine parameters while parts are being delivered. Results from preliminary analysis were also used for comparisons with actual experimental results.

V.1 STATION-KEEPING MODEL

A simple station-keeping controller model was developed in order to design the control system. In the conceptual model, the buoy was considered as a floating body being acted upon by the viscous drag of water, in which the controller minimized the distance to target coordinates. The controller was to be implemented through software using available Arduino libraries meant for Servo motor control, then programmed onto the ESP32 microcontroller. The ESP32 translated force input in Newtons to pulse waves that the ESC module connected to the propellers reads as movement commands. Table 2 shows how the ESC module interprets these commands

Table 6. ESC Movement Commands read from PWM inputs

Pulse-Width of Input	**ESC Movement Command**
1000-1500 μs	Move backwards
1500 μs	Stop
1500-2000 μs	Move forwards

Since the nature of the problem requires calculating the necessary force in real-time, a PID controller was implemented so all information about positional change is taken into account. PID controllers work best for real-time disturbance rejection since it predicts and corrects for future error. This helped with latency that could come with wireless communication and ensured there is no steady-state error when given enough time to self-correct.

The free-body model used to design the control system is shown in Figure 3, along with the relevant forces and errors in Table 5. The premise was that since the buoy propels itself with a differential thruster system, the mechanics would be similar to robot vehicles such as USVs (unmanned sea vehicles). Being a common problem, there were already many existing solutions for modeling differential-drive vehicles. Namely, many of the techniques used in [7] were utilized to model the kinematics of the buoy. [7] showcases a unicycle model with independent linear and angular velocities, which perfectly aligned with the buoy's mechanics. However, the buoy model was able to be more simplified than what is shown in [7]. Since the final heading error is irrelevant, the system only needs to correct the angular error towards zero rather than the buoy needing to face a certain direction in its final position. This transformed the model into the following equations for forward thrust $F_T = F_R + F_L$ and differential thrust $F_D = F_R - F_L$:

$$F_T(t) = m\frac{dv}{dt} - D_V v(t) \tag{1}$$

$$F_D(t) = \frac{I}{R}\frac{d\omega}{dt} - \frac{D_\omega}{R}\omega(t) \tag{2}$$

where m is the total mass of the buoy, I is inertia, R is the distance from the center of the buoy to its thruster, and v and ω are linear and angular velocities respectively.

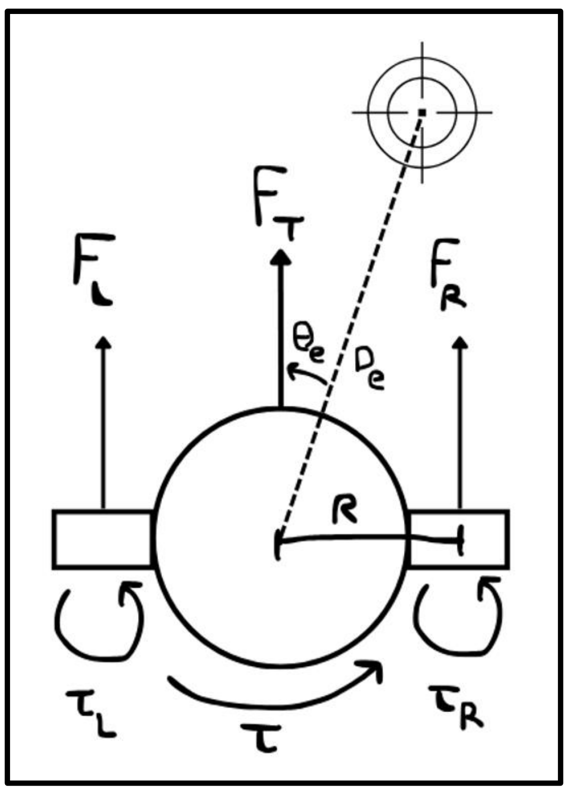


Figure 3. Simplified free-body diagram for SAMB. Buoy is facing upwards with a dashed line towards the target position

Table 7. Labels for forces and parameters shown in Figure 3.

Symbol	**Force**
F_L	Left thruster force
F_R	Right thruster force
F_T	Forward thruster force
τ_L	Torque from left thruster
τ_R	Torque from left right
τ	Total torque
Symbol	**Error**
D_e	Distance error towards target
θ_e	Heading/Angular error towards target

As seen in equations (1) and (2), the model only accounts for total linear and angular drag resistance, and simplifies the drag forces into a velocity-based force scaled by the drag coefficients: D_V for linear drag, and D_ω for angular drag. Real marine vessels need to account for pitch and roll, as well as wind resistance, but these were omitted as modeling these parameters proved too complex to model for this project, and the sensors required for measuring such parameters fell outside this project's budget.

Since linear velocity and angular velocity are independent in this model, the SAMB used two decoupled control systems that control forward speed and angle respectively. These both could be derived from the error parameters in Table 7. Thus, the plant for the distance control system inputs forward thrust force F_T, and the plant for the heading control system inputs the differential thrust force F_D. The transfer functions for both plants are shown below:

$$P_D(s) = \frac{D_e}{F_T} = \frac{1/m}{s^2 - \frac{D_v}{m}s} \tag{3}$$

$$P_\theta(s) = \frac{\theta_e}{F_D} = \frac{R/I}{s^2 - \frac{D_\omega}{I}s} \tag{4}$$

Analysis was done in Matlab's Multisim program. PIDTuner was used to determine the PID controller parameters. The distance control system and the step-response is shown in Figure 4. The response achieves around 15% overshoot with a rise time of around 10 seconds. The speed of the response was limited by the control signal needing to stay under 32 N of force, or the maximum combined thrust of the propellers.

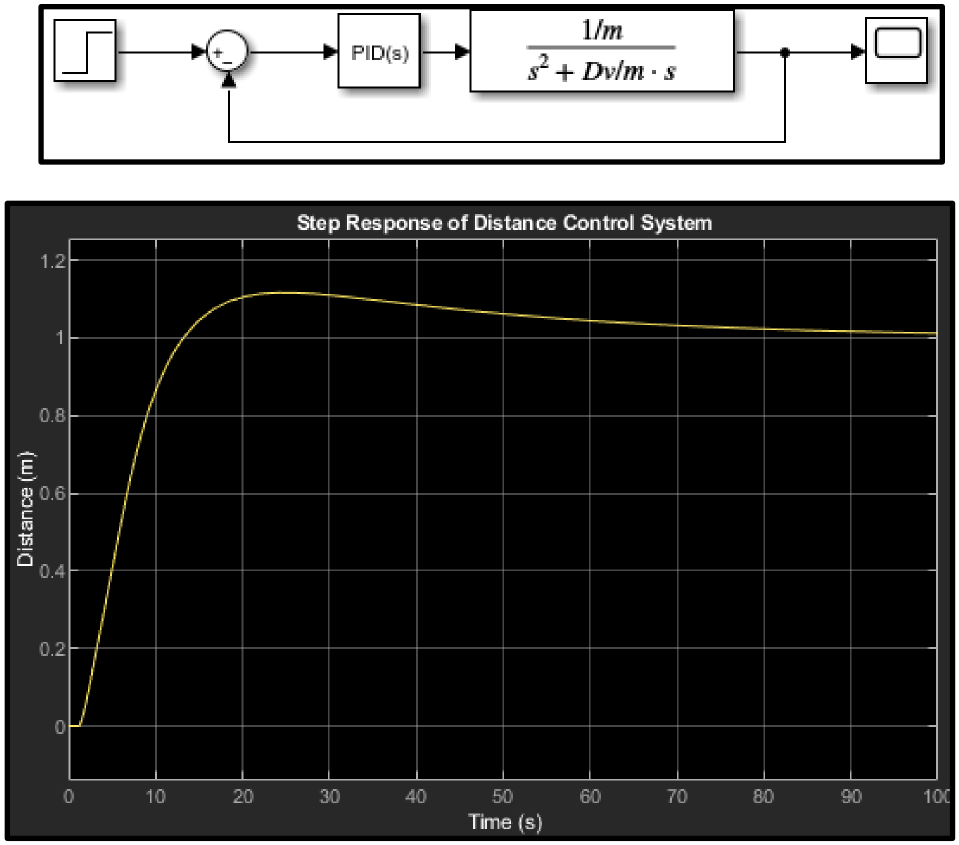


Figure 4: Matlab PID tuner and step response for distance control system.

V.2 ENERGY AND ENDURANCE

The calculated power storage of the chosen power source would be around:

$$12V * 100ah = 1200Wh \qquad (5)$$

The above-calculated energy would serve as the foundation for estimating the endurance time. The low-power electronics consisting of the GPS module, communications system, microcontroller, computer system, and beacon light would use a low continuous power rating compared to the thrusters.

The propulsion system uses a high power consumption rate but only at specific instances when the need arises for course correction. Since the buoy is not supposed to move continuously like boats, its endurance is highly dependent on the duty cycle of the thrusters. When the positioning error is minimized, then deadband control comes in handy, hence minimizing the number of times the thrusters will run, thus increasing endurance. The solar panel increases endurance by regenerating some of the consumed energy during daytime hours.

It should be noted that the actual endurance will depend on several factors such as weather conditions, current strength, sunshine, and control behavior. However, the chosen power subsystem provides more support for the project objective than a pure battery system without power generation capabilities.

VI. TESTING & EVALUATION

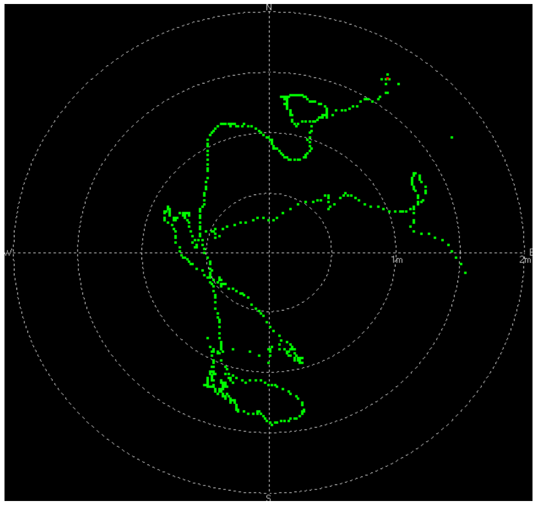
For testing purposes, two testing levels were implemented on the Smart Anchorless Marker Buoy prototype: subsystem testing and prototype testing. As SAMB comprises several systems such as power supply, embedded control, GPS navigation, communication, propulsion, and structure, it was important to test the performance of the prototype at both the component level and as an entire system. Testing aimed to ensure successful operation of each subsystem and the entire system as a prototype but also to determine the limits and integration issues of SAMB.

Testing was performed in several phases. In the first phase, testing of component-level functions of individual subsystems such as the LoRa modules, GPS module, and propellers was carried out, with the exception of the power and control subsystems since these would be covered in the integrated test. After successful completion of individual subsystem tests, overall system testing took place in order to verify if the SAMB components can properly exchange data and work under certain operational conditions.

VI.1 SUBSYSTEM TESTING.

GPS and Communication Tests

GPS subsystem testing consisted of two parts: letting the GNSS receiver run standalone and verifying that coordinate information could be transmitted to the control hardware. Testing primarily entailed observing the GPS deviation map as the antenna sits idle indoors with multiple wireless signals nearby. Since this test covers the worst-case scenario, being able to still maintain an accuracy of under 3 meters would ensure accuracy for all other situations. This test also would prove the update rate of the receiver. U-Center. a software to analyze u-blox GPS receivers, was used to evaluate the receiver for the two tests. The results are shown below in Figure 5.



Measurement	Accuracy (m)
Radial Error Goal	**3.000**
Horizontal Positional Error	1.398
Vertical Error	2.088
2D Ellipse Error	0.93, 0.55

Figure 5. *Indoor GPS deviation map over 10 minutes (above). GPS accuracy statistics (below).*

Testing of the communication subsystem involved using the LoRa-based communication hardware to send position-related information from the buoy electronics to another receiving station, such as a user's computer. In particular, this involved checking whether coordinate information and status information could be packaged and successfully sent to the receiving end. As communication was not a concern in this project because of the use of LoRA over WAN, the successful sending of position packets constituted sufficient testing of the communication subsystem.

Actuator Testing

Testing of the propulsion system involved connecting the thrusters to their ESCs and checking whether they can be controlled. As a result of the test, it was confirmed that thrusters were capable of producing thrust as required and were controlled using the chosen electronics. In addition, given the amount of power thrusters consume, this step was also important for energy management.

Structural and Safety Testing

Testing for the structural subsystem was done through inspection and assembly. It was established that the PVC frame would have been able to support the mounted components and retain the necessary physical configuration for the buoy. Waterproof junction boxes and pass-throughs were assessed to establish that the components within the buoy would not be damaged when exposed to moisture and other external factors. The beacon light was also tested to prove that it would help to identify the buoy.

VI.2 INTEGRATED SYSTEM TESTING

Once the functionality of each subsystem had been confirmed, integrated testing of the system was conducted to assess how well the whole prototype operated as one integrated system. This involved confirming that the buoy was capable of powering itself up, obtaining GPS data, transmitting its telemetry, and responding with propulsive controls without significant interference between subsystems. Power consumption and error-correction was recorded as shown in Figure 6 in varying water speeds.

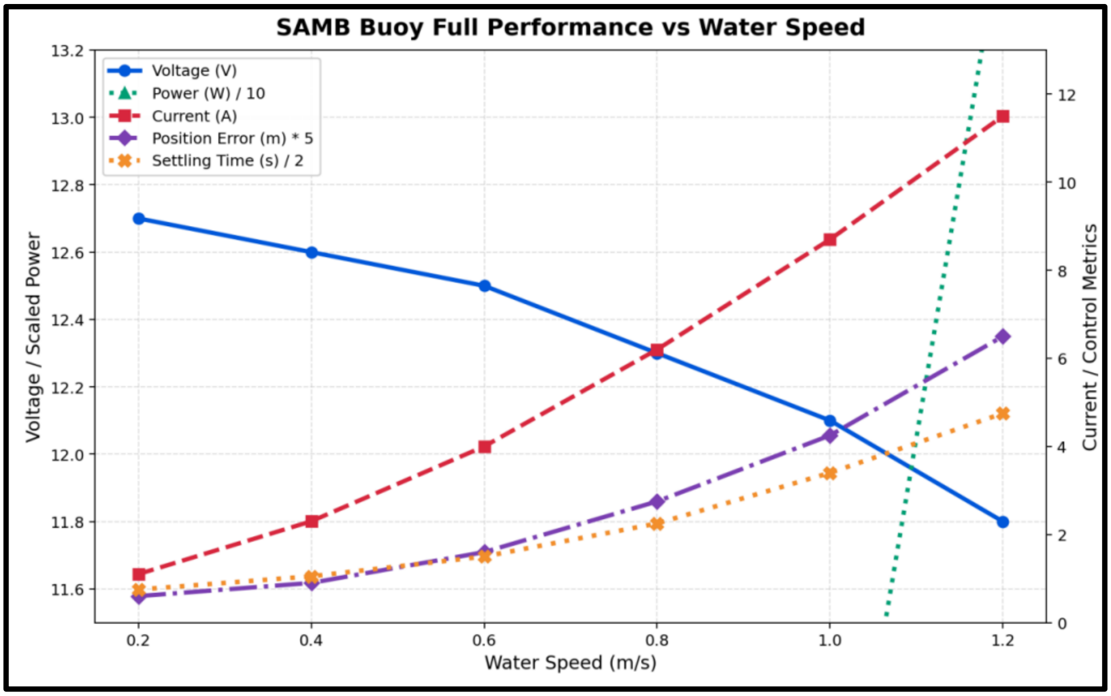


Figure 6. *Integration testing for the full SAMB system done over varying water surface wave speeds.*

The integration testing showed that the architecture used was able to support simultaneous operations between different subsystems. The control board was able to receive GPS data and transmit information via the wireless link. Similarly, the propulsion hardware was able to function under the control structure. However, the power consumption increased dramatically with increasing wave speed. This was expected since higher wave speeds needs to be combated by higher constant speeds. The SAMB architecture proved to be functional in low-speed conditions, which meets the requirements for handling shore conditions.Since the prototype was constructed based on the restrictions of the senior design course sequence, the integrated testing was mainly geared toward proving the feasibility of the concept rather than qualifying it for maritime applications.

VI.3 TESTING LIMITATIONS

Although the testing process showed how feasible the SAMB design was, there were some constraints with regard to the range of testing that can be done due to time constraints. It is not possible to test for many times in the field nor for longer periods of endurance due to constraints in project timelines. Particularly, the testing for power consumption had to be omitted for the previously stated reasons.

Also, since real-life situations in the ocean will consist of fluctuating currents, wind, and wave motion, along with GPS, it is difficult to fully reproduce such an environment in an academic project setting. Therefore, the tests conducted during this project can only be regarded as prototype level testing.

VI.4 RESULTS

Station keeping, prolonged operation due to battery and solar power, periodic telemetry transmission, and visible operation in outdoor conditions were among the initial project objectives. The project was highly successful in accomplishing its objectives, as evidenced by the previous results for testing done on the prototype.

- The control system corrects for under 10% overshoot and less than 30 seconds of settling time.
- GPS provides a radial accuracy of four meters.
- Actuators can maintain thrust forces of 16.7 N each.

- The power subsystem can maintain full thrust for wave speeds under 2 m/s.

On the other hand, there was partial verification of some goals at the prototype level. Long-term endurance and accurate position holding capability under environmental disturbances will have to be tested further. Hence, while the final outcomes indicate that the SAMB concept is feasible, it needs further improvement before claiming full performance at the deployment level.

Table 8. Quantitative performance objectives and results.

Objective	**Expected**	**Actual**
Position error	±3 m	~2-4 m
Runtime	14 days	Limited testing duration
Transmission rate	Every 5-10 seconds	Every 1-2 seconds
Thruster force	~32 N	29.4 N

As a whole, the Smart Anchorless Marker Buoy proved to be a successful senior design project. The project team created and incorporated all of the necessary technologies for the creation of an anchorless buoy system. Furthermore, it showed that it is indeed possible to create an anchorless buoy system using readily available parts along with embedded processing, energy harvesting capabilities, and electric propulsion.

VIII. BROADER IMPACTS

VIII.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 [8]. 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.

VIII.2 LIFELONG LEARNING

Working on this project brought several educational benefits for the group. The group interacted with several industries through this project: signal processing, mechanical design, electronics, water-tight systems, and more. The project helped broaden the team’s skillset in these industries and additionally in team-collaboration. The design process modeled how professional engineers create, iterate, test, and present new products. The team also learned how to balance costs with quality. Researching also familiarizes the team with current industry standards and how to navigate ethical guidelines. The project also encouraged creative thinking and problem solving.

VIIII. CONCLUSION

From the Smart Anchorless Marker Buoy project, we were able to prove the viability of the concept of employing embedded control, global positioning, wireless telemetry, and propulsion in building an anchorless buoy that would allow such a buoy to self-regulate its position in water. This was accomplished through the culmination of efforts from different aspects of engineering that include power electronics, communication, control systems, embedded systems, and structural mechanics into one unified system. With the completion of this stage, the project went from mere theory to concrete realization of a working proof-of-concept.

In essence, this design proved that an anchorless buoy is indeed possible through commercially available materials and the implementation of a subsystem-based approach. Power subsystem gave the electrical basis of the buoy, GPS and LoRa subsystems provided means to obtain and transmit the location data of the buoy, the control subsystem gave a working way to control the movement of the buoy, and finally, the structural subsystem served as the physical body for the rest of the prototype. These results showed that we have accomplished our main aim, i.e., designing and implementing a prototype for a smart anchorless buoy.

X. APPENDICES

APPENDIX A. BILL OF ITEMS

Table 9. 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:	
Rasberry Pi 3	$35.00
ESP32	$10.00
IMU Module	$10.99
Movement Subsystem:	
Thrusters & ESC kit	$189.00
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
Structural / Extra:	
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	Donated
3 phase wire bulkhead connectors	$10.99
2 phase wire bulkhead conectors	$10.99
Waterproof Passthrough Connectors	$23.98

Unknown costs	$350.00
Price Per Unit:	$1,110.00

APPENDIX B. ARDUINO CODE FOR LORAWAN COMMUNICATION

The below code was modified from [9], the official Heltec repository containing an example for parsing GPS location data and sending it through LoRaWAN. The Heltec TinyGPS++ library and LoRaWAN library provided by [9] were used. The code communicates with The Things Network, a service that provides a webpage GUI and user-friendly API to set up LoRaWAN. The OTAA app key is redacted for security.

```
#include "LoRaWan_APP.h"
#include "Arduino.h"
#include "HT_TinyGPS++.h"

TinyGPSPlus GPS;

/* OTAA Parameters for TTN console */
uint8_t devEui[] = {0x22, 0x32, 0x33, 0x00, 0x00, 0x00, 0x00, 0x23};
uint8_t appEui[] = {0x70, 0xb3, 0xd5, 0x7e, 0xd0, 0x07, 0x71, 0xe3};
uint8_t appKey[] = {[redacted]};

/* LoRaWAN Configuration */
uint16_t userChannelsMask[6] = { 0x00FF, 0x0000, 0x0000, 0x0000, 0x0000, 0x0000 };
LoRaMacRegion_t loraWanRegion = ACTIVE_REGION;
DeviceClass_t  loraWanClass = CLASS_A;
uint32_t appTxDutyCycle = 15000;
bool overTheAirActivation = true;
bool loraWanAdr = true;
bool isTxConfirmed = true;
uint8_t appPort = 2;
uint8_t confirmedNbTrials = 4;

static void prepareTxFrame(uint8_t port) {

  pinMode(Vext, OUTPUT);
  digitalWrite(Vext, HIGH);

  float lat = 0.0, lon = 0.0;
  Serial.println("Waiting for GPS...");

  while (!GPS.location.isValid()) {
    uint32_t start = millis();
    do {
      if (Serial1.available()) {
        GPS.encode(Serial1.read());
      }
    } while (GPS.charsProcessed() < 10);

    // Timeout check
    if ((millis() - start) > 10000) {
      Serial.println("No GPS data received: check wiring");
      break;
    }
  }

  lat = GPS.location.lat();
  lon = GPS.location.lng();

  digitalWrite(Vext, LOW); // powers off for faulty or no detection of GPS data, saves power

  // Payload initialization
  appDataSize = 0;
  unsigned char *puc;
```

```
  puc = (unsigned char *)(&lat);
  appData[appDataSize++] = puc[0];
  appData[appDataSize++] = puc[1];
  appData[appDataSize++] = puc[2];
  appData[appDataSize++] = puc[3];

  puc = (unsigned char *)(&lon);
  appData[appDataSize++] = puc[0];
  appData[appDataSize++] = puc[1];
  appData[appDataSize++] = puc[2];
  appData[appDataSize++] = puc[3];

  Serial.print("LAT: ");
  Serial.print(lat, 6);
  Serial.print(", LON: ");
  Serial.println(lon, 6);
}

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

  Serial1.begin(38400, SERIAL_8N1, 33, 34); // baud rate could be different for NEO-M9N, ensure this
first

  pinMode(Vext, OUTPUT);
  digitalWrite(Vext, HIGH);

  Mcu.begin(HELTEC_BOARD, SLOW_CLK_TPYE);
}

void loop() {
  switch (deviceState) {
    case DEVICE_STATE_INIT: {
#if(LORAWAN_DEVEUI_AUTO)
      LoRaWAN.generateDeveuiByChipID(); // Arduino could be set to generate the DevEUI key
automatically
#endif
      LoRaWAN.init(loraWanClass, loraWanRegion);
      LoRaWAN.setDefaultDR(3);
      break;
    }
    case DEVICE_STATE_JOIN: {
      LoRaWAN.join();
      break;
    }
    case DEVICE_STATE_SEND: {
      prepareTxFrame(appPort);
      LoRaWAN.send();
      deviceState = DEVICE_STATE_CYCLE;
      break;
    }
    case DEVICE_STATE_CYCLE: {
      txDutyCycleTime = appTxDutyCycle + randr(-APP_TX_DUTYCYCLE_RND, APP_TX_DUTYCYCLE_RND);
      LoRaWAN.cycle(txDutyCycleTime);
      deviceState = DEVICE_STATE_SLEEP;
      break;
    }
    case DEVICE_STATE_SLEEP: {
      LoRaWAN.sleep(loraWanClass);
      break;
    }
    default: {
      deviceState = DEVICE_STATE_INIT;
      break;
    }
  }
}
```

Figure 7.   Arduino code for Heltec ESP32 Lora V4

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