MicroFloats: Swarmable, Autonomous Underwater Vehicles for Oceanic Studies

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ME/ECE 4723 A – Capstone Design

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Table of Contents

Executive Summary

Saline lakes and the deep ocean remain some of the most mysterious and least understood environments on the planet. But their remoteness can act as a remarkably good analog for the study of conditions on distant worlds like Titan, Enceladus, and Europa, worlds that may harbor microbial life like that which exists in harsh terrestrial environments. Specifically, a better understanding of methane cycling due to biotic processes could provide valuable insights into the relationship between observed methane emissions on other celestial bodies and their potential for supporting life. Ocean scientists wish to examine large volumes of water and generate three-dimensional spatial maps to gain a better picture of ocean chemistry and how it relates to methane; this is impractical with single UAVs. Instead, the scientists need small, inexpensive, and autonomous robotic floats that can be deployed in coherent swarms, each float responsible for characterizing a column of water.

The so-called "MicroFloat" will need to fit standard Sonobuoy dimensions, measuring under 4⅞ inches in diameter and under 36 inches long. Additionally, the MicroFloat will need to incorporate a buoyancy control system to descend and ascend in the water at a rate of roughly 0.5 meters per second. It must routinely dive to and operate at depths of up to 750 meters. The float will also need to be able to collect methane data as well as other relevant metrics like pH and salinity over the course of its minimum two-week mission, after which the float must surface and transmit its data to its operators. The primary design goal is to create an autonomous robot that is robust, power efficient, and easily serviceable that can consistently withstand oceanic conditions and reliably collect data. The vehicle will also need to be cost-effective to maintain its viability in large production numbers, as opposed to existing commercial solutions that are large, expensive, and not easily scalable in quantity.

After exploring a variety of novel concepts, the team selected a solution that uses a cylindrical form factor with a bottom-mounted oil bladder (as part of the oil-driven buoyancy control system) and external top-mounted sensors, which best synchronizes customer requirements and engineering design specifications. The oil is pumped into the bladder, changing the vehicle's volume without changing its overall mass, allowing the MicroFloat to alter its buoyancy and therefore depth in the water. This buoyancy control system has already been proven successfully in numerous marine robots. The design must maintain strong battery life, withstand pressure cycling from diving to maximum depth and resurfacing while remaining easy to fabricate, operate, and maintain. The team has worked out a detailed design and has conducted extensive stress, fatigue, buoyancy, buckling, and sealing analyses to ensure it will meet all required specifications.

To validate the design analyses, the team has constructed a functional, full-size prototype to test in a real-world aquatic environment. The full-size sensor packages are not included due to budget constraints and the scope of this first prototype, and for the purposes of the initial test were replaced with a simple

pressure sensor to allow the control system to operate properly. A new bladder system made from readily available items at a small fraction of the price of similar custom setups was successfully tested outside of the vehicle with the provided buoyancy engine. This bladder system remained watertight when submerged in water and was free of any hydraulic leaks. With the bladder fully deflated and with the addition of stabilizing weights to account for the missing sensor mass, the prototype was positively buoyant at the surface and remained upright. However, an overlooked manufacturing defect in the aluminum housing cylinder put one end out of round, which prevented the primary O-rings from sealing properly and allowing water to get inside the vehicle. Testing was immediately aborted to avoid potential water damage to electrical components. Nevertheless, the design concept was successfully validated and requires additional prototype iteration to solidify the practical implementation. Future work for this project will include further testing to determine if weight must be added for desired stability and ability to descend in the water, research into how to best account for manufacturing tolerance in the roundness of the aluminum cylinder, the development of a more robust control system, and an implementation of true swarm behavior and communications. An updated internal housing design using aluminum plate and standoffs in place of 3D-printed components should also be explored.

Glossary

- Al 6061: A precipitation-hardened aluminum alloy containing magnesium and silicon as its major alloying elements, often used for structural application due to its high strength and corrosion resistance
- ASTM: American Society for Testing and Materials
- CTD: Sensor for determining the conductivity, temperature, and depth in water, a primary instrument for determining essential physical properties of sea water
- CWA: Clean Water Act
- EPA: United States Environmental Protection Agency
- GPS: Global Positioning System
- NPT: National Pipe Taper, a US standard for tapered threads used for pipe and related fluid fittings that utilizes thread deformation and sealants to form leak-free connections
- PCB: Printed Circuit Board
- pH/ORP: Sensor for measuring the pH and the oxidation reduction potential of a surrounding fluid
- PMEC: Pacific Marine Energy Center, the research institute that developed the "μFloat"
- RUR: Rossum's Undergraduate Robotics, the most recent capstone design team to work on the MicroFloat project
- UAV: Underwater Autonomous Vehicle

1. Introduction and Background

The deep ocean and hypersaline lakes present some of the most mysterious environments on the planet. Theses harsh, remote conditions support microbial life, as evidenced by methane cycling in the aquatic ecosystem, and a better understanding of this process can provide valuable insight into the relationship between methane emissions and the presence of life. High concentrations of methane have been observed on the distant ocean worlds of Titan, Enceladus, and Europa, and these moons are of great interest to astrobiology. The team's task is to create a small autonomous float that can be deployed in swarms to sample and record data regarding methane, pH, salinity, and other relevant metrics over large areas of water. Each quasi-Lagrangian float will use a buoyancy engine to ascend or descend in the water while passively riding underwater currents to traverse laterally. Collectively, the swarm will generate a time-evolving, three-dimensional spatial map of a volume of water that would be impractical to map using commercially available UAVs, providing ocean scientists with valuable data on large-scale ocean chemistry.

The vehicles will explore methane seeps in Mono Lake, California, a hypersaline lake, as well as in the Gulf of Mexico. This project aims to design the electrical and mechanical systems for a single unit scalable to large numbers. The main challenges faced in this design include waterproofing, withstanding high pressure and high corrosion for extended periods, and developing robust communications to reliably transmit collected data for analysis. The proposed solution has a cylindrical form factor that does not exceed 4⅞ inches in diameter and is roughly 36 inches in length, with top-mounted external sensors and a bottom-mounted enclosed oil bladder. The vehicle must be able to change its depth by using a buoyancy engine that redistributes mass in the form of oil flow to alter density and volume and therefore buoyancy force. Key performance specifications include functioning at a depth of 750 meters, enduring continuous missions for at least two weeks, and the ability to change altitude at 0.5 meters per second. Watertightness of the design and its ability to change its buoyancy are critical and will be tested in a pool using a functional prototype built to full-scale mechanical and electrical specifications. The building of the prototype will also validate the design's manufacturing feasibility. In the remainder of this document, prior art and applicable patents are presented and discussed. The codes, standards, customer requirements, and engineering considerations are detailed, which are used as a steppingstone to potential solution concepts. A preliminary design is systematically selected and justified, and detailed mechanical analysis is presented to refine and validate the concept. To further validate the concept, a prototype was created and tested. The results, future work, and project deliverables are described below to illuminate a path forward.

2. Existing Products, Prior Art, and Applicable Patents

Previous work on this MicroFloat project is well-documented and outside organizations have made similar vehicles in the past for independent research. Advanced float and buoy systems like the MicroFloat are not in high demand and are often desired for a very specific area of study, so in the past such systems were created in house by the researchers who needed them. However, there are still some commercially available options on the market.

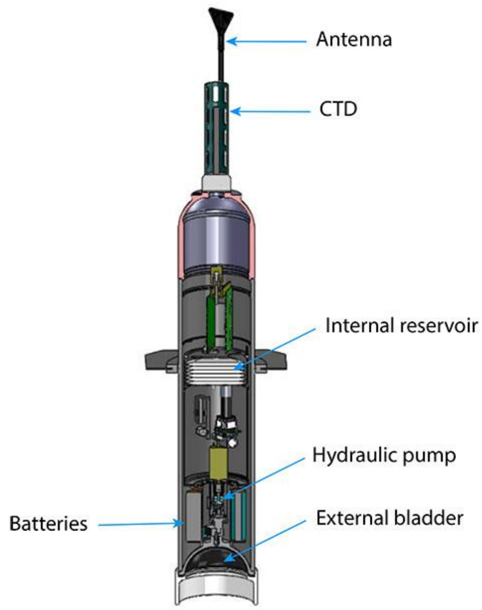

Figure 1. Section view of the Argo float system displaying primary internal components [1].

The Argo float, shown in Figure 1, was created by the Multi-National Argo Organization, which has worked with over 50 research agencies to make a float system for surveying the ocean. The Argo float can operate for years with little to no maintenance, diving to depths up to 2,000 m and rising to the surface to submit the data it collects via satellite communication [2]. The float uses a patented buoyancy engine design that incorporates a piston and hydraulic pump.

Below, Figure 2 shows the Navis Profiling Float, developed and sold by Sea-Bird Scientific. The Navis Float uses a piston-based pump to displace oil into an external reservoir and can operate up to pressures of 2000 dbar (roughly 2900 psia). This product also has an air bladder that inflates at the surface to provide excess buoyancy to ensure that the GPS module can receive the best signal strength. It is high-powered and its batteries can last for up to 300 CTD profiles. However, it is a large unit, significantly larger than the Sonobuoy profile required of the MicroFloat, and operates on a fixed ten-day cycle where it descends to full depth and ascends back to the surface with little flexibility.

Figure 2. The Sea-Bird Scientific Navis Profiling Float, utilizing a mechanical displacement pump for its buoyancy engine and an external air bladder for better surface communications.

Built on the Navis Float architecture is the Seatrec SL1, which was developed in partnership with Sea-Bird Scientific. The SL1 is depicted below in Figures 2 and 3. It is also a large form factor float extension, coming in at nearly five feet in length and 55 pounds in weight. The SL1 is designed to supplement Argo Float-like vehicles by providing them with a consistent power source. The unit leverages a unique energy harvesting system that takes advantage of naturally occurring temperature differences, using the Solid-to-Liquid phase change of specially selected materials to convert the ocean's thermal energy into electrical energy and outputting up to 2.2 Wh per cycle. The SL1 can be used exclusively to power a profiling float up to 1000 meters in depth, offering an alternative to range-limited rechargeable batteries.

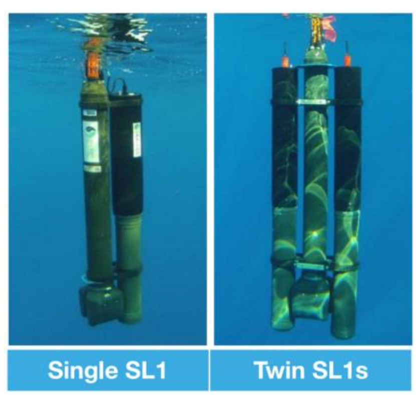

Figure 3. The Seatrec SL1, which can be deployed in single or dual configurations. It is powered by a novel energy harvesting device that generates electrical energy for the vehicle.

Figure 4. The NKE ARVOR I, a midrange “standard” float offered by NKE that collects CTD and pressure data and can operate at depths up to 2000 m.

NKE Instrumentation offers a lineup of profiling floats with varying capabilities for a wide range of applications. One such float, the ARVOR I, is shown above in Figure 4. NKE is involved in the international Argo program and aims to offer a range of “standard” profiling floats that can collect CTD data with the option to integrate other types of sensors like pH and dissolved oxygen. Data is transmitted via a satellite network. The lineup offers shallow floats for depths of 400 meters or less alongside deep floats rated for up to 4000 meters. The NKE lineup offers a great base platform but is likely not economically feasible at large scales and may not be able to support swarm behavior and communication.

Figure 5. The Teledyne Marine APEX BioGeoChem float, a large and robust vehicle designed to support biogeochemical profiling for various research applications.

The Teledyne Marine APEX BioGeoChem float is another commercial float designed to support a wide variety of applications (Figure 5). It can accommodate CTD, dissolved oxygen, and pH sensors as well as a fluorometer. It is a large vehicle, measuring 6.5 inches in diameter and 55 inches in length. This float is unique among the competing commercial floats as it offers an optional carbon fiber hull over the standard aluminum. Both are rated for a depth of 2000 m.

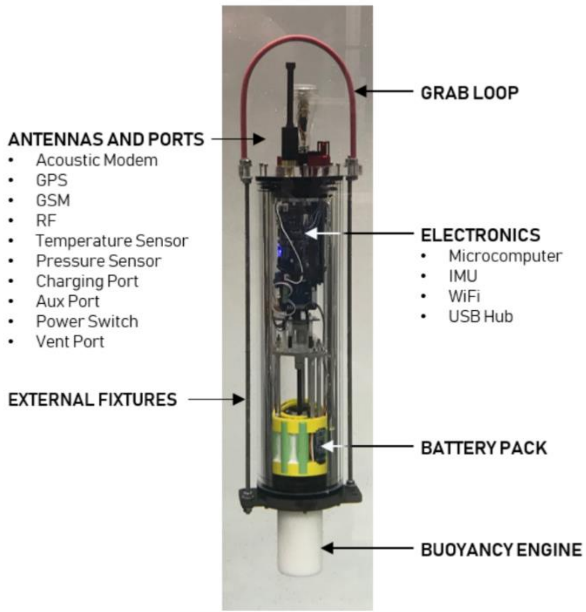

Figure 6. Image of a prototype µFloat unit detailing its primary subsystems and components [2].

Another design, dubbed "µFloat", is shown above in Figure 6. The µFloat was created by PMEC, an umbrella organization that works with several research and development programs, to study the oceans and other water ecosystems. Notably, their project page states that the µFloat project was designed for lakes, so it is intended for shallow bodies of water and is not capable of reaching large depths. The float alters its buoyancy using a lead screw. The µFloat tracks itself using acoustic modems located on GPS-trackers on nearby buoys.

Previous design teams at Georgia Tech have also worked on the MicroFloat project. The Lagrangian Profiler MK4 is shown below in Figure 7. The Lagrangian Profiler MK4 was developed by a Georgia Tech VIP team. The buoyancy system relies on an oil-driven piston. The piston has a large area open to high pressure, which necessitates more force to move the piston. The system pressurizes oil to change the vehicle's density, thereby changing its buoyancy and causing it to ascend or descend.

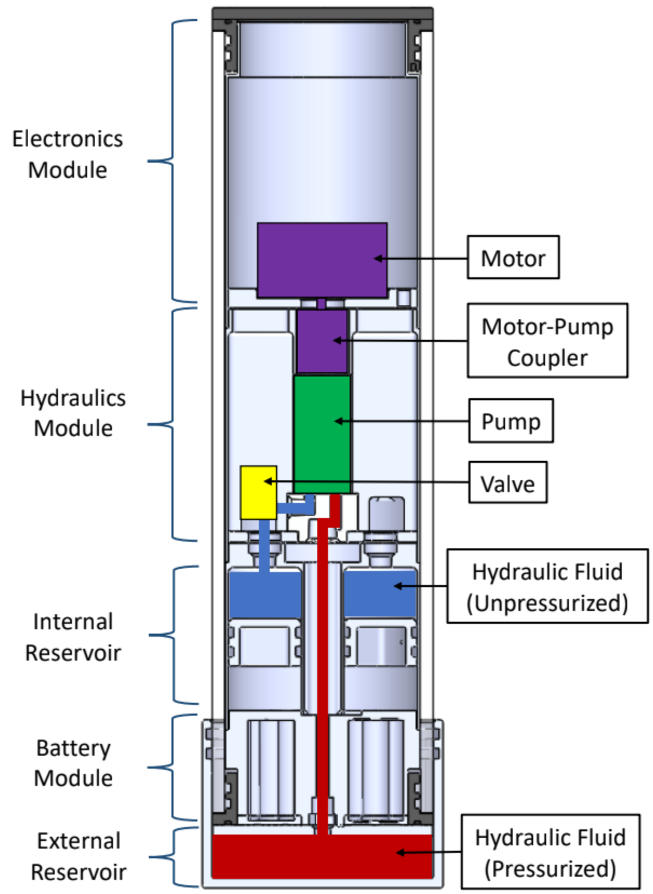

Figure 7. Cutaway view of the Lagrangian profiler developed by a Georgia Tech VIP team [3].

"Together We Swim" developed a new style of hydraulic buoyancy engine. The design was never physically validated due to sealing issues. However, the team did fully develop the design and an exploded view of the assembly model is presented in Figure 8.

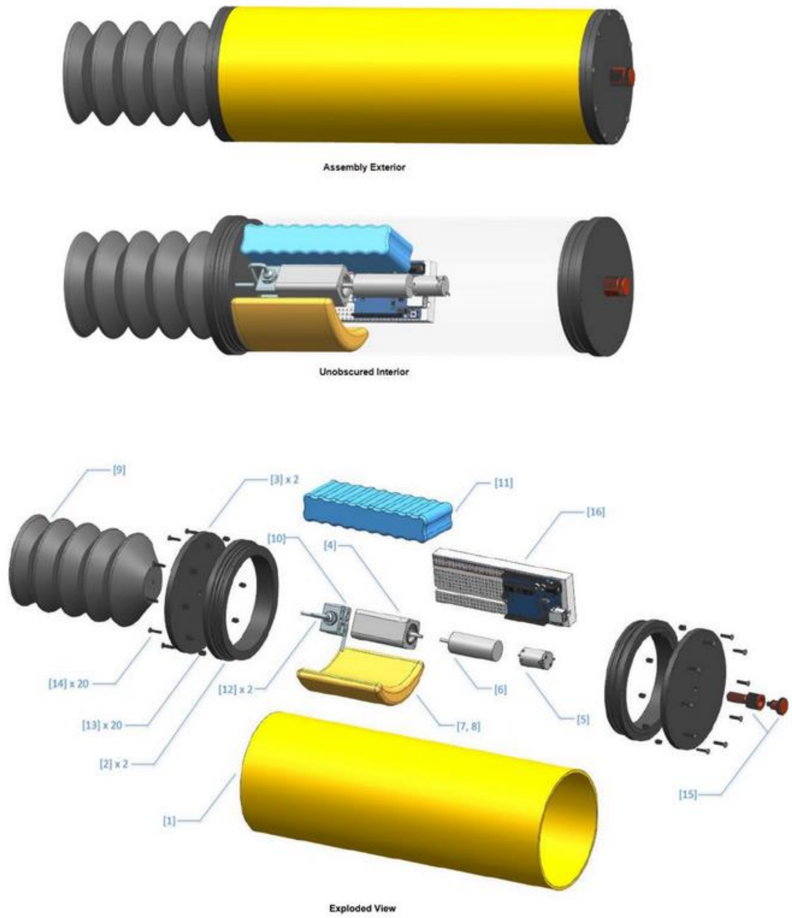

Figure 8. Assembly model of buoyancy engine developed by "Together We Swim" [4].

Rossum's Undergraduate Robotics (RUR) completed the most recent iteration of the MicroFloat design. Their design used an oil pumping system with an external bellows for buoyancy control. It also used commercial parts designed for underwater use in underwater robotics to ensure waterproof sealing. Figure 9 depicts a model of RUR's final design with the cylindrical casings removed.

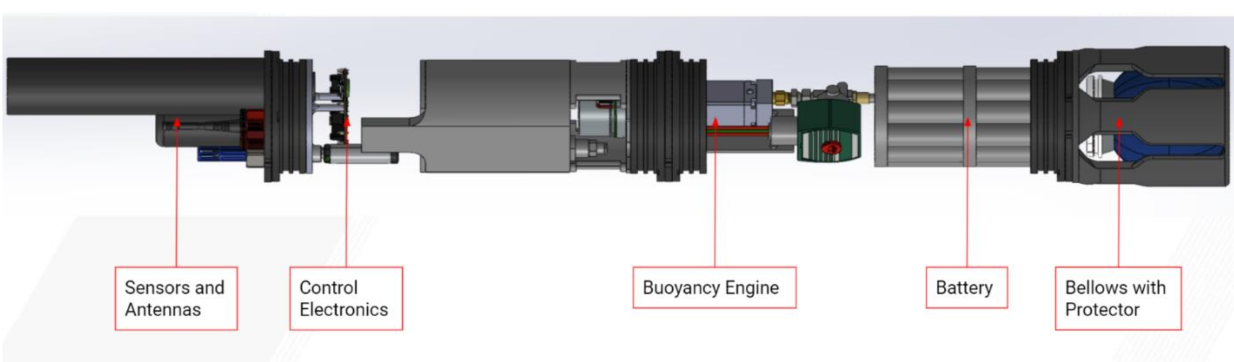

Figure 9. Rossum's Undergraduate Robotics MicroFloat prototype design [5].

3. Codes and Standards

The team has identified four areas of code and standards that are relevant to the design. These are codes related to corrosion resistant and marine fouling by casing, codes related to marine hydraulic systems, codes related to toxic impact on aquatic life, and codes related to usage of heavy metals.

Standard Practice for Exposing and Evaluating Metals and Alloys in Surface Seawater is governed by ASTM G52 – 20. It describes the requirements and recommendation to evaluate corrosion and marine fouling behavior of materials exposed to a saltwater environment [6]. This would be helpful in providing guidance on the level of corrosion resistance and choice of material to develop specification for our micro-float to reduce harm to aquatic life and withstand saltwater conditions. Standard specification for seal-less lube oil pumps with oil through the motor for marine applications is documented by ASTM F2798-09(2018). It lays out the requirements applicable to design, construction and testing of seal-less, rotary positive displacement pumps with oil-through motors for marine operations [7]. This would be helpful to ensure our hydraulic system can function reliably in saltwater environments and does not pose a potential threat to aquatic creatures.

The use of antifouling paint is regulated by the Administration of EPA and only certified paints that are qualified antifouling paint containing organotin may be used. This requires the paint to have a release rate of no more than 4.0 micrograms per square centimetre per day. The organotin compounds released is also governed by section 304(a) of the Clean Water Act (CWA). It states that to avoid chronic toxic effect to aquatic life in saltwater, the release rate should be lower than 0.0074 µg/L measured on a four-day average, and the limit should not be exceeded more than one year. At the same time, to protect saltwater aquatic life from acute toxic effects is 0.42 µg/L. This criterion is implemented as a one-hour average, not to be exceeded more than once every three years on the average. [8] According to the RoHS standard that which has been adopted by some states in the US, including California, New Mexico, New York and Rode Island, the restrict of heavy metals are <0.1% by weight for lead mercury, hexavalent chromium and cadmium. However, in California, the limit for cadmium is less than 0.001% by weight. [9] These two codes must be taken into consideration when choosing the paint or material coating to be used on the other surface of the MicroFloat.

4. Customer Requirements and Engineering Design Specifications

Discussions with stakeholders, understanding of the problem, and application of the solution yields an insight into the requirements to be fulfilled by engineers. Filling out a House of Quality is a systematic way to weigh the engineering requirements in terms of customer requirements. Since the purpose of the robot is to leverage oceanic currents while altering buoyancy and studying methane seeps at depths up to 750 meters, those requirements are the most important, reflected by a score of 10 in the House of Quality as shown in Figure 6. It is worth noting that the depth stated as a requirement is 1000 m, which includes a conservative estimate of conditions. Measurement of pressure to calculate neutral buoyancy, ease of fabrication, battery life of at least 2 weeks, and ease of operation are secondary requirements essential to cost-efficient usage of the robots; however, since they do not directly prevent underwater study, their importance varies between 6 and 8. Finally, soft requirements mainly aimed at logistics include size and cost. These requirements are suggestive more than constraining, thereby carrying the importance of 5 and respectively. Finally, 'swarmability' encompasses the ability of the robots to communicate with each other and share data within a specific range, as well as interpret and execute instructions received. These functionalities, while crucial to the overall goal of the project, are outside the immediate scope of Mechanical Engineering, and can be easily incorporated into most solutions through collaboration with Electrical Engineering points of contact. Swarmability is therefore given an importance of 2.

The matrix in Figure 10 weighs the impact of engineering requirements of interest in terms of the customer requirements. Every column has at least one strong connection, indicating that each engineering requirement is crucial to at least one customer requirement, and is not an unnecessary consideration draining allocation of resources. Altering buoyancy, ease of operation, and ease of fabrication are the only customer requirements which do not have a strongly relevant engineering requirement as all three of the requirements are mainly agnostic to the properties of the material or design and is more dependent of the implementation of mechanisms and choice of design in terms of manufacturing capacity. When accounting for importance associated with each customer requirement in addition to the correlation between the customer and engineering requirements, the weighted sum along the columns determines the importance of each engineering requirement, providing a ranking system for engineering requirements by priority. For example, getting the correct sensor precision is the most important requirement to fulfill for successfully accomplishing the project at 17%, followed by minimizing the cost with importance of 15%, and maximizing battery life, which lies at a close 14% relative importance.

Category	Weight	Customer Requirements (Explicit and Implicit) \ Engineering Requirements	Tensile Strength (Mpa)	Compressive Strength (Mpa)	Sensing Range (m)	Motion Range (# cycles)	Mass (kg)	Cost ($)	Battery Life (weeks)	Resolution
		Column #	1	2	3	4	5	6	7	8
		Direction of Improvement	▲	▲	▲	▲	▼	▼	▲	◇
Sensing	10	Measure Methane Seeps								●
	8	Identify Pressure upto 1500 psi								●
Size	5	As Small as Possible	▽	▽		○	●	●	○	
Longevity	10	Withstand Ocean conditions 1000m deep	●	●				○		
	7	>2 week battery life			▽	●	▽	○	●	
Budget	4	<$800 budget	▽	▽		○	○	●	○	
Primary Applications	2	Swarmability			●			○	▽	
	10	Alter buoyancy	▽	▽		▽	▽		○	
	6	Easy to Operate			○	○	▽		▽	
	8	Easy to Fabricate	▽	▽			○			
		Target	15	15	1000	1000	75	800	2	1/10R
		Max Relationship	9	9	9	9	9	9	9	9
		Technical Importance Rating	117	117	43	118	104	138	128	162
		Relative Weight	13%	13%	5%	13%	11%	15%	14%	17%
		Weight Chart								
		Column #	1	2	3	4	5	6	7	8

Figure 10. Comparison of relationships between customer requirements and engineering specifications in a House of Quality.

Relative importance of the engineering requirements assist prioritization when analyzing synergies and interferences. As shown in Figure 11, cost and battery life interfere with several other requirements but take a higher priority in the decision-making process.

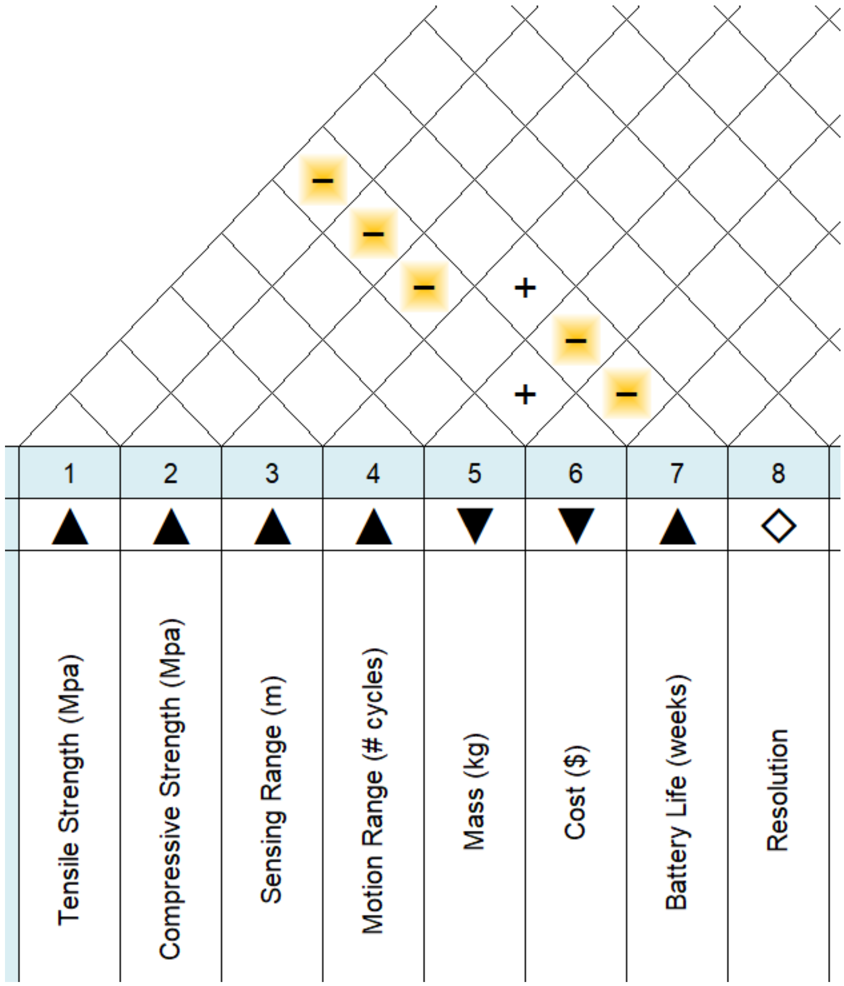

Figure 11. Synergy and interference evaluation in the roof of the House of Quality.

After understanding the engineering implications of customer requirements, a specification sheet could be generated, outlining all aspects of the robot to consider. As shown in Table 1, the specification sheet can be used to divide responsibilities to enable collaborative parallel progress. Responsibilities are assigned to team members based on individual strengths and expertise and are subject to change as dictated by the project timeline. The specification sheet outlines the overarching requirements that drive the design through its iterations and define the framework for the MicroFloat.

Table 1. Specification Sheet

D/W	Requirement	Source
	Operation	
D	Withstand hydrostatic pressure at depths up to 750 m	Research Project PIs and Dr. West
D	Alter buoyancy to float on surface and dive to or ascend from any depth up to 750 m	Project Scope
D	Completely seal internal components from water	Project Scope
D	Minimum two-week mission time	Research Project PIs and Dr. West
D	Measure methane, pH, ORP, and CTD	Research Project Proposal
W	Support flexible sensing options (mechanically and electrically) and allow individual sensors to be turned on or off	Research Project Proposal
D	Send and receive signals from surface	Project Scope
D	Use GPS to broadcast position	Project Scope
	Geometry	
D	Cylindrical form factor (A-size sonobuoy); 4.875" diameter, 36" length	Research Project PIs and Dr. West
	Material	
D	Resist corrosion; maintain surface quality and no loss of mechanical strength	Project Scope
	Cost	
W	Inexpensive unit price relative to commercial UAVs; $800	Research Project PIs and Dr. West

Finally, after a thorough understanding of customer requirements in terms of engineering accountabilities, design ideation can be initialized through generation of independent functions determining the success of the robot. A function tree for the vehicle is shown in Figure 12. Spread across four major categories of surviving ocean conditions, navigating underwater, collecting data, and communicating with base units, are 18 subfunctions to ensure the successful fulfillment of the primary need of studying methane seeps and salinity through vertical profiling of the ocean. Together, the House of Quality, Specification Sheet, and Function Tree provide a direction to evaluate any designs and solution implementations in terms of customer requirements. These tools are crucial to evaluate designs and decisions in terms of customer requirements rather than intuition or biased opinion by quantifying requirements and their relations.

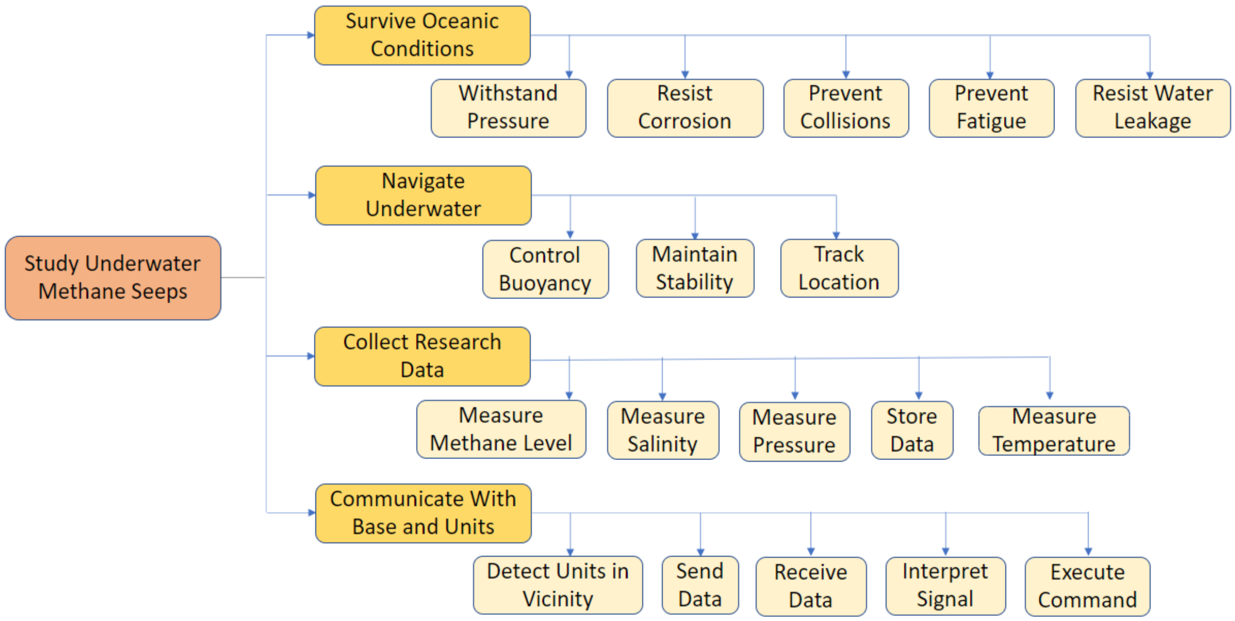

Figure 12. MicroFloat function tree delineating the major sub-functions necessary to complete ocean research missions.

5. Market Research

The MicroFloat project is sponsored by Dr. West from the ECE department at Georgia Tech. Dr. West, and indirectly the ocean scientists he collaborates with, is the only customer for this product. The market is small and focused and implies a very specific set of needs, so the most effective form of market research is receiving direct feedback on the team's design, as well as gaining insights on the strengths and weaknesses of prior attempts on this project, presented as prior art in this document.

The intended price point for each unit is roughly $800 to ensure that a large swarm may still be economically viable to researchers on limited budgets. Because it exists in such a niche market, the MicroFloat can be customized to a great extent as a flexible platform. There is currently no commercial product like the MicroFloat; similar vehicles have only been made in research and university settings as one-off design experiments.

Regular meetings with Dr. West provide the team with feedback on the design and any desired areas of improvement, so there is a constant line of communication open to ensure that the client will be satisfied with the final product. Dr. West also serves as the team's liaison to the ocean scientists that will ultimately deploy the MicroFloats in the Gulf of Mexico.

6. Design Ideation

After identifying the current product alternatives on the market along with the customer requirements laid forth by Dr. West, the team moved onto design ideation and produced 6 different concept ideas. Based upon the previous discussions, the team agreed upon a set of functions that all of the designs were required to provide; these include the following overarching functions: the MicroFloat needs to withstand the harsh oceanic conditions demanded of it, it needs to navigate under the water to different depths and locations, it needs to collect the required research data, and finally it needs to be able to communicate with the researcher's computer along with other floats nearby. Each of these main functions have additional subfunctions, but for the sake of brevity they can be found in the function tree (Figure 8) located above. Ultimately, these functions are imperative to the project goal of studying underwater methane seeps.

To facilitate the ideation process, the team constructed a morphological chart to help identify different design concepts that could achieve the desired functionality laid out in the function tree. The morphological chart, as seen below in Figures 13a and 13b, accounts for each of the subfunctions from the function tree and presents at least three distinct possibilities for fulfilling each function. The morph chart is also divided into sections corresponding to each of the broader system functions.

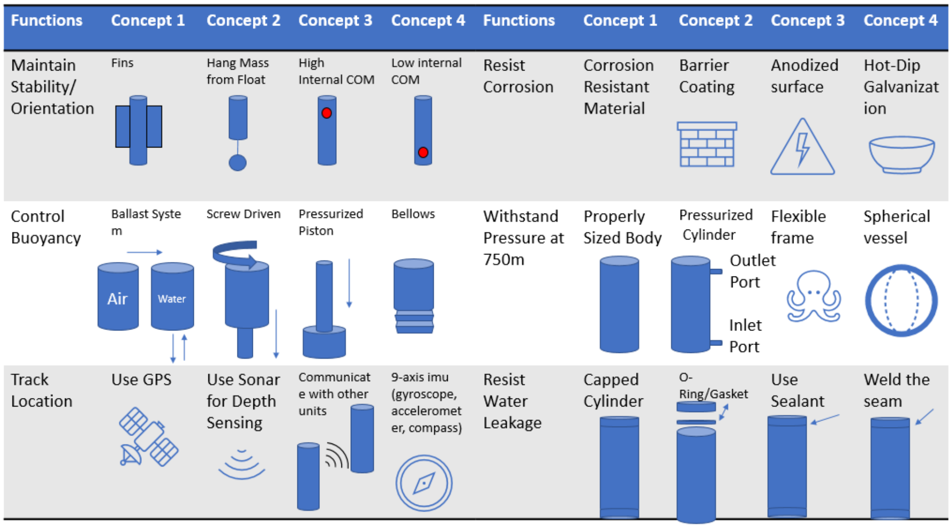

Figure 13a. First half of morphological chart used in ideation process, capturing design ideas for the specified functions.

Functions	Concept 1	Concept 2	Concept 3	Concept 4	Functions	Concept 1	Concept 2	Concept 3	Concept 4
Store Sensor Data	Save to SD card	Save to usb-drive	Save to micro-computer storage		Send and Receive Signals	RF module + Antenna	Sonar Module	Wi-fi Emitter	
Support Multiple Sensors	Multiple inputs on controller	Sufficient Cap Space	Integrate additional sensors onto pcb	Universal connector port	Convey Position and Sensor Readings	Read Stored Data and Send it	Get current sensor readings and Post	Transmit data when surfaced	Storage device retrieved by scientists
Support Universal Mounting	Interchange able Sensor Nodes	Standardized waterproof connectors			Prevent Collisions	Light to Signal Status	Sonar to Detect Floor	Thrusters for X and Y movements	

Figure 13b. Second half of morphological chart used in ideation process, capturing design ideas for the specified functions.

The first grouping of concepts in the morphological chart are dedicated to navigation and movement of the MicroFloat through the targeted ocean regions. The main considerations here regard the stability of the system in the water, the system's ability to change its buoyancy to change its current position, and its ability to track its location during operation. For stability, finned and finless designs were considered for helping to maintain the unit's orientation during operation. Buoyancy control is arguably one of the most important subfunctions of the entire system; this is due to the fact that other forms of locomotion become infeasible to implement at the depths required for this system and buoyancy engines become the choice means of controlling motion in the ocean depths. The four conceived concepts for this category are using a piston to displace water from within the cylinder confines, using a ballast system as seen in conventional submarines, using a screw-driven piston, and using an oil-pump to expand and contract a bellow. Each of these methods introduce system-specific complexities, but the oil-driven bellows system is known to be effective as it is used in other deep-sea systems for similar applications. Lastly, the location tracking can be solved by using an array of sensors ranging from conventional GPS hardware to using pressure or sonar sensors to derive the depth of the unit.

The second group of design concepts focus more on the mechanical and material designs necessary for enduring the ocean conditions over the unit’s period of use. These concepts include the unit's ability to resist corrosion during a two-week exposure to saline water, the ability to withstand up to 750 m of pressure, and the system's ability to resist water ingress during operation. Corrosion resistance can be achieved through either selecting a corrosion resistant material such as stainless steel or by applying some additional process that provides a layer of protection to the otherwise susceptible base material. The choice of material and type of corrosion resistance will be mostly driven by cost for this project. Withstanding both water ingress and high-pressure surroundings are just as important to the success of this project as buoyancy control and much consideration will be devoted to both. To handle the high water pressures, the material, body geometry, stress concentrations, and internal pressurization need to be considered. The solutions range from rigid hollow cylinders and spheres to flexible non-compressive sphere structures. The concepts for ingress protection were assorted between replaceable end sections for either a sphere or cylinder body, to using more permanent sealing methods, such as using a waterproofing sealant or welding the body shut.

The last two function groupings were more design agnostic with respect to the physical design of the MicroFloat since the solutions for data collection and communication are mostly a matter of selecting the correct sensors and components for the electronics system. Additionally, most of the concepts in this area do not drive the overall design of the MicroFloat and overlap in their utility to the system. This means that more of the design concepts in this section are more likely to be implemented into the final design as there isn't a need to necessarily choose certain concepts over others like in the mechanical design section. An example of this would be ensuring that there is sufficient space for sensing components on the unit's body along with providing additional sensor connections on the main control board. Most of these concepts can be flexibly added or altered during the PCB design phase but currently most of these features are intended to be implemented in the final design.

From the function requirements in the function tree and the potential solutions ideated in the morphological chart, the team composed six different integrated concepts for the MicroFloat design. Each of the following concept designs tentatively fulfill the functions laid out in the function tree. The designs can be split into two types based on geometry: cylindrical and spherical. The first concept, depicted in Figure 14 below, uses a cylindrical shell as its body and a screw-driven piston to change the displaced volume of the float to change the buoyancy of the system.

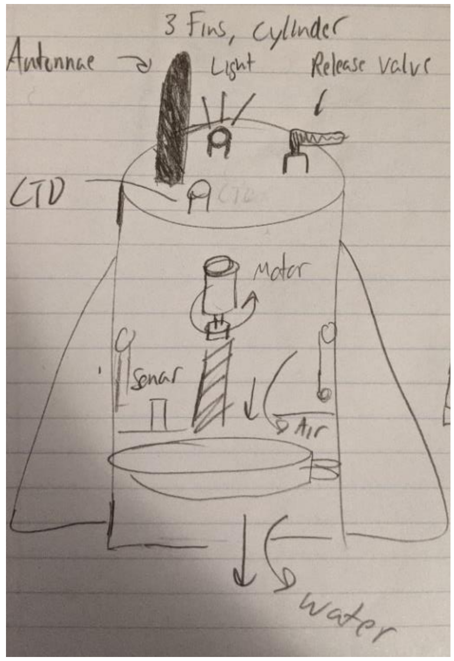

Figure 14. Concept sketch of a cylindrical and finned design using an electric motor to mechanically drive a piston, drawing in or expelling seawater to alter the device's mass and therefore buoyancy.

The ends of the cylinders are sealed by a set of caps with double O-ring seals to ensure watertightness. Additionally, this system employs fins to reduce changes in axial rotation, but reducing axial rotation is not as important as reducing axial translation for the stability of the system. The next design concept, presented below in Figure 15, also utilizes a cylindrical base but includes additional components to add to the structural rigidity and watertightness of the design.

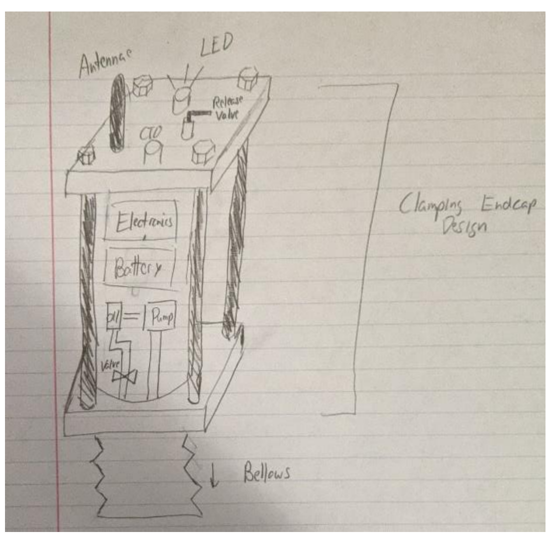

Figure 15. Concept sketch of a cylindrical design with an oil-driven hydraulic bellows and clamped plate endcaps.

The square endcaps are clamped against the cylinder via bolted connections with the additional threaded rods. This guaranteed clamped force will help create a proper seal by properly compressing an O-ring at the ends of the cylinder. Additionally, this should improve the ease of performing maintenance and testing on the unit by making it easier to assemble and disassemble. The system's depth is controlled by an inflating or deflating bellow to change the distribution of mass within the vehicle and thus its buoyancy. The final cylindrical design concept, illustrated below in Figure 16, changes the location of the bellows to being in the center and separates the unit into two halves. One half of the cylinder is dedicated to the electronic subsystems while the other is used to hold the buoyancy drive and batteries. This design choice allows for the potential to swap the electronics and sensing section independent of the buoyancy engine.

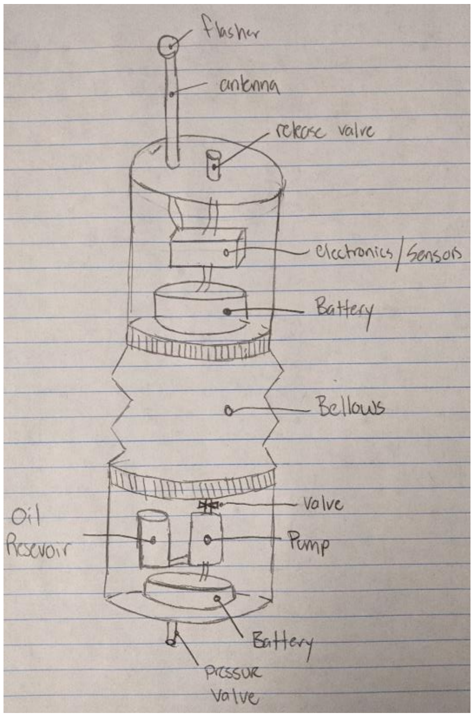

Figure 16. Concept sketch of a cylindrical design with a centrally located hydraulic bellows. The design incorporates a degree of modularity by separating the control and sensing electronics from the hydraulic and actuation hardware.

The remaining design concepts each employ a spherical geometry, but with considerably different implementations of the shape and shell design. The first spherical concept employs two shelled halves that clamp together with a flange to ensure a watertight sphere, shown below in Figure 17.

Figure 17. Concept of a flanged spherical design with an external oil sack serving a purpose similar to that of a hydraulic bellows.

The seal between the hemispheres can be made with either an O-ring or a gasket. The buoyancy engine is similar to designs two and three as it also uses an oil-driven bellow. The second spherical concept is the most unique of the concepts as it uses a flexible body in lieu of a rigid metal body to withstand the high ocean pressures. A sketch of this design is presented in Figure 18.

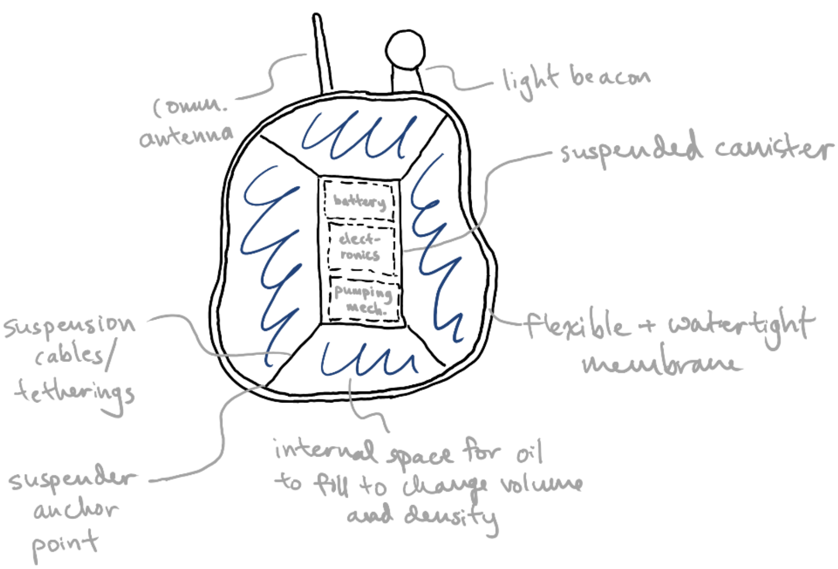

Figure 18. Concept sketch of a nonrigid balloon design that can deform with external forces. Control electronics and hardware are suspended inside an internal canister, and hydraulic oil fills the cavity between the canister and the surrounding membrane.

Its spherical shape allows for an even distribution of the pressure throughout the body, and the internals can be filled with an incompressible fluid such as oil to maintain its volume across different depths. Like previously described designs, the soft membrane concept uses an oil-pump to drive changes in buoyancy, but this would be done by transferring oil from an internal shell that stores and pumps oil for buoyancy changes. The final spherical concept utilizes a composite design between the other spherical designs, represented in Figure 19 below.

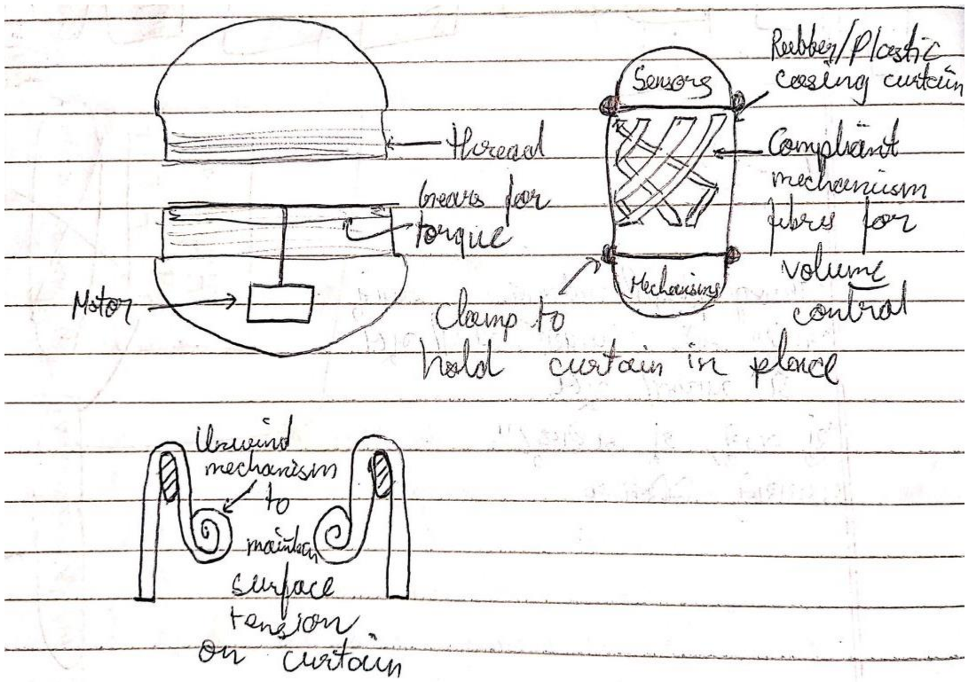

Figure 19. Concept sketch of a spherical design utilizing a centrally located hydraulic bellows. The design includes a novel compliant mechanism to actuate the bellows.

This design is composed of two spherical halves with a set of bellows in the middle. As a means of changing its internal volume, an internal compliant mechanism is shifted between several discrete states that then translates the two halves into successive positions. This compliant mechanism would be actuated by a motor to change the displaced volume of the unit.

7. Preliminary Concept Selection and Justification

The generated concepts are compared using an evaluation matrix to determine the best designs to move forward with. The evaluation matrix hinges on a set of criteria based on the vehicle's required functions, with each criterion also assigned a relative importance from 0 to 10 (higher is more important). The team discusses each concept to give it a rating, also from 0 to 10, with higher being better, for each criterion. This rating is multiplied by the importance value for its associated criterion to obtain a relative weighted score. A concept's weighted scores for all criteria are summed, and this sum determines the ranking of concepts from best to worst for this application. The evaluation matrix comparing the described concepts is presented in Table 2.

Table 2. Evaluation Matrix for Concept Ranking and Selection

Criteria	Importance	Bottom Piston		Bottom Bellows		Middle Bellows		Sphere Sack		Soft Balloon		Compliant Sphere	
		Rating	W. Total	Rating	W. Total	Rating	W. Total	Rating	W. Total	Rating	W. Total	Rating	W. Total
Measure methane seeps	10	10	100	10	100	10	100	10	100	10	100	10	100
Identify pressure up to 1500 psi	8	10	80	10	80	10	80	10	80	10	80	10	80
As small as possible	5	6	30	6	30	6	30	8	40	9	45	8	40
Withstand ocean conditions at 1000 m	10	7	70	8	80	7	70	10	100	10	100	9	90
Two-week battery life minimum	7	8	56	8	56	9	63	6	42	6	42	6	42
<$800 budget	4	9	36	8	32	8	32	4	16	2	8	6	24
Swarmability	2	0	0	0	0	0	0	0	0	0	0	0	0
Alter buoyancy	10	4	40	8	80	8	80	8	80	8	80	5	50
Easy to operate	6	6	36	8	48	9	54	5	30	2	12	5	30
Easy to fabricate	8	7	56	9	72	6	48	5	40	2	16	4	32
Total		504		578		557		528		483		488	
Relative Total		0.160611855		0.184193754		0.177501593		0.168260038		0.153919694		0.155513066	
Rank		4		1		2		3		6		5	

The most crucial criteria are assigned a relative importance value of 10, including the ability to measure methane seeps, alter buoyancy, and withstand ocean conditions for an extended time at 750 m below the surface. These criteria are most important because they are essential to the vehicle's successful functioning; if the vehicle cannot perform any of these tasks, the design fails in its mission, so these criteria should have the highest weight in selecting from potential designs. The absolute winner is the cylindrical design with a bottom-mounted bellows and clamped endcaps (Figure 15). This design is most similar to the one pursued in previous work by RUR. However, the cylindrical design with a central bellows (shown in Figure 16) and the spherical design with an external oil sack (shown in Figure 17) also performed well in the matrix and took second place and third place, respectively, warranting further investigation into feasibility.

The screw-driven piston and soft balloon concepts are notable for their innovation but break down upon any realistic analysis due to practicality and manufacturing challenges. For example, at full depth, the piston would require a linear actuator considerably larger than the vehicle's cylindrical boundary dimensions to supply an adequate amount of torque to turn the screw, while the membrane of the soft balloon as well as the internal canister suspension have no obvious, easy, or cost-effective solutions or even material choices. The compliant sphere concept is also innovative, but compliant mechanisms fall outside the scope of practicality for this course and are generally unproven. Compliant actuators, however, could inspire a custom folding bellows design.

The cylindrical design with the bottom-mounted bellows, the winner from the evaluation matrix, earns the highest ease of fabrication score, which makes it the most practical to prototype. It is also the closest in design to RUR's prototype, which has already been proven effective. However, a potential drawback of this design is that it is not hydrodynamic at all in comparison to RUR's design, so it will need a visual rework, potentially with circular endcaps that route the threaded rods through the cylindrical housing rather than around the outside of it. This will also prevent the rods from being exposed to the marine environment and corroding over time. The alternative cylindrical design with the middle-mounted bellows is a runner-up, and with its built-in modularity, its greatest strength is in ease of operation and maintenance for the operator and potential for longest or most expandable battery life, since it utilizes two separate batteries. However, this concept scored very similarly overall to the bottom-bellowed cylindrical design despite being slightly more complex; separating the control and sensing electronics from the buoyancy engine is not a critical feature, so the tradeoff in complexity and difficulty in manufacture compared to the bottom-bellowed design could present practical challenges that are ultimately not worth a design that could end up with about the same or only marginally better performance.

The last runner-up is the flanged sphere with an external oil sack. A spherical design is more compact and hydrodynamic than a cylindrical one and may also be more space-efficient internally. With a simple bolted external flange, disassembly is also more straightforward than removing endcaps and extracting hardware. However, the external reservoir may offset the benefits in hydrodynamics from using a spherical design and could result in vertical instability as the vehicle attempts to dive or resurface. It may need a controller for self-righting, which will add another layer of complexity that the cylindrical designs do not have. Furthermore, this design is much more difficult to manufacture and is less practical than the other winning concepts.

Based upon the rankings and further research into sealing methods, it was decided that a cylindrical design would offer the best compromise between mechanical performance, usable volume, and manufacturability, while still meeting all other engineering requirements. In turn, the team decided to hybridize concept designs two and three by using the cylindrical body and endcap sealing method of concept three and placing the oil bellows at the bottom of the MicroFloat for increased stability as seen in concept two. Additionally, the cylindrical design of the body simplifies component mounting solutions both internally and externally and should provide a conventional and ergonomic design for operator usage. These design decisions have informed our overarching design and the resulting external CAD model can be seen below (Figure 20).

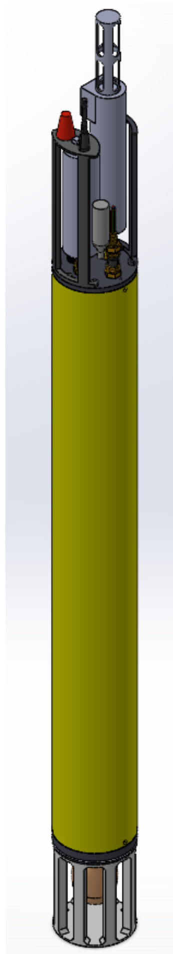

Figure 20. MicroFloat CAD assembly model.

The following sections will cover the design principles and analysis used in determining the final mechanical and electrical design of the MicroFloat. The engineering analysis was critical in deciding the driving dimensions and material selection for this design. Additionally, the internal layout and electrical design were influenced by the size constraints determined in the analysis. Ultimately, these considerations along with others informed the finalized design and will be covered in greater detail in the following sections.

8. Industrial Design

Although the design is not meant for widespread common consumer use, we still implemented and applied multiple Industrial Design considerations to make the MicroFloat a more user-friendly experience that will improve the workflow of those using it. Two of the main focuses during the design of the MicroFloat were adhering to irreducible simplicity and making the design intuitive to use. During the design process, this meant that we identified the simplest solutions that did not compromise on the functionality of the design. This can be directly seen in the shape of the MicroFloat; its overall form reduces to a simple, yet understandable figure – a vertical cylinder. The handles point upwards along with all of the sensors and communications equipment to give a directional line of sight. The bottom on the other hand is flat and is the only flat surface on the entirety of the MicroFloat and intuitively can be understood to be a ground plane. This base geometry gives rise to an understanding of the inherent, intentional orientation of the MicroFloat, which is to have its sensors pointing upwards out of the water for the viewer to identify during the retrieval process.

The visual hierarchy of the MicroFloat itself may bely itself to being more intuitively understood and used, however, its use case also precludes a need for high visibility for collection purposes. To accommodate this need, the MicroFloat not only utilizes its visual hierarchy to draw the eye, but it also utilizes high contrasting colors to draw the eye to it even when surrounded by ocean waves. The colors chosen for its body are a bright yellow for the main body and a dark black for the end caps and handles. For additional visibility, a high intensity led flasher is installed atop the sensors to grab the user's attention as well. These visual cues make the MicroFloat more distinctive from not only a marketing standpoint but also from a usability standpoint during the collection process.

Beyond the visual aspects of the MicroFloat, the physical design also dedicates itself to being efficiently ergonomic and useful for the end-user, whether they are performing maintenance or actively using the MicroFloat. The handles for the MicroFloat act as both a cage for the sensors, but also as an easy mounting point to hook the MicroFloat when retrieving for data transfer. The bottom bellows cage acts as a stand, so you can vertically stack multiple MicroFloats next to each other. Possibly the most useful and ergonomic feature of the MicroFloat is its internal modularity. The electronics for data logging and depth control are attached to the top cap, whereas the mechanical hardware and oil reservoir are attached to the bottom cap. This division of components makes repair and maintenance much easier, as it allows you to work on the components that you need without having to take apart the entire assembly. Overall, the MicroFloat has been designed with Industrial Design principles at its core, as it is well understood that for a product to perform well, it needs to be not only functional, but designed with human use in mind.

9. Engineering Analyses and Experiments

The main power analysis is shown below in Figure 18. The power, energy, and heat produced by each electrical component. If every part is left to run for 24 hours, 42.93 Wh will be used by the float. However, not every component needs to be powered constantly. Only the sensors, I2C chip, SD card, and microcontroller need to be powered constantly which totals out to 23.29 Wh per day. The GPS, Bluetooth, and RF transmitter need to be powered when resurfaced which power totals out to 0.24 W. The motor, which is our second biggest energy draw after the sensors, turns on whenever need for example getting to/staying at the testing depth, diving, or resurfacing.

Table 3. Electrical power analysis, broken down per component

Type	Component	Quantity	Voltage(V)	Current(A)	Power (W)	Energy 1 Day (Wh)	Heat (W)
Communcation	RF Transceiver Module:	1	3.3	0.03	0.1	2.4	0.5495083
Microcontroller	ESP32-DEVKITC-32D	1	5	0.03	0.01584	0.38016	0.5495083
Motor	DC Motor	1	12	12	144	15	2.7475413
GPS	GPS Module	1	3.6	0.045	0.068	1.63	1.8683281
Sensor	pressure sensor	1	12	0.02	0.25	6	0.8792132
Sensor	Meathane	1	12	0.12	1.44	10.6	0
Sensor	PH sensor	1	12	0.01	0.12	2.88	0
i2c chip	i2c chip	1	5	0.15	0.075	1.8	0.8792132
Data Storage	SD Card	1	3.3	0.1	0.33	2.0625	0.33
Communcation	Blue Tooth	1	5	0.00144	0.0072	0.1728	0.47564
Total			61.2	12.50644	146.40604	42.92546	8.2789523

The individual weight of the components included in the MicroFloat are tabulated in Table 4. The total weight of all electrical and mechanical components for the full scale MicroFloat is 5850 g. However, some of the sensos cannot be acquired for our prototype due to cost constraints. Models of theses sensors will be used instead while weights will be attached to them in order to simulate the actual weight distribution for the full scale MicroFloat design. The design calculations will be done using an internal component weight of 6435 g. This will allow for a 10% margin of error for the weight of internal components as well as to account for fasteners that will be used.

Table 4. Estimated component weights, given in grams.

Part Type	Part Name	Quantity	Total Weight (g)
Electrical Componenets			
RF Transceiver Modules and Modems	Adafruit Industries LLC 3070	1	50
Microcontroller	ESP32-DEVKITC-32D	1	100
Pump	Takako TFH-040 pump	1	270
Pressure sensor	DST CTD	1	30
Motor	625857 Maxon	1	350
Battery	Bioenno BLF-1206A 12V, 6Ah	1	700
Methane Sensor	Franatech METS Methane CH4 Sensor	1	800
Motor Controller	ICQUANZX DC 5V-36V 15A 3-Phase Brushless Motor Speed Controller Motor Control Board	1	88
Diode (Battery to 5v)	BZX55C5V1-TAP	2	10
connectors	PCB Terminal Blocks, Header, Wire-to-Board, 4 Position	2	10
Battery Terminal Block Connectors	Phoenix Contact 1757019	1	5
Resistor (100 ohms)	R1	2	10
PH sensor	SBE 27 pH/O.R.P (Redox) Sensor	1	700
GPS Module	NEO-6M GPS module	1	50
protptype sensor	Bar30 High-Resolution 300m Depth/Pressure Sensor	1	100
i2c chip	I2C Level Converter	1	50
Mechanical Components			
6061 Al Tube (Main Body)	OD 4.5", wall 0.24" * 36 in	1	5116.08944
Brass Hex Nipple	40142318	1	100
Brass Threaded NPT Male with Zinc-Plated Steel Nut	51235K127	1	100
6mm to 8mm Flexible Clamping Shaft Coupler	4002-0006-0008	1	44.8
6061 Al Bar (End Caps)	4.5" diameter, 5" length	2	1387.8
Oil Reseviour		1	50
Hydraulic Oil (800m)	Hydraulic oil for high pressure operations	1	640
SubConn® Circular Connectors	Underwater wire connectors (6 pins and 8 pins)	2	200
		Total Weight (Excluding outer Tube)	5845.63

To ensure that the MicroFloat design will be able float on top of the water surface, calculations were performed to determine the required displacement to stay neutrally buoyant. This was done using an internal component weight of 6435 g while the outer shell will be made using a 4.5 inch (114.3 mm) 6061 aluminum cylindrical pipe with a wall thickness of 3.175 mm. The exposed volume of the methane sensor and pH/O.R.P. sensor were also taken into account in the calculation of the effective displacement. The calculations were derived from the neutral buoyancy condition where:

$$mass\ of\ water\ displaced = tatol\ weight\ of\ microfloat$$

$$mass\ of\ water\ displaced = total\ outer\ voume\ of\ microfloat * density\ of\ sea\ water$$

$$tatol\ weight\ of\ microfloat = Aluminum\ shell\ weight + total\ weight\ of\ electrical\ and\ mechanical\ components$$

The results of the calculations performed are tabulated in Figure 20 and it shows that to achieve neutral buoyancy, the design must have a minimum aluminum casing length of 0.62 m (24.32 in). This signify that our design with aluminum casing length of 36 in can achieve neutral buoyancy as the additional displacement created by the current design can be counteracted by the addition of weight near the bottom of the MicroFloat thus it is not of concern.

Table 5. Buoyancy Calculation Results

Properties	Aluminum - 6061
Material Density (g/cm^3)	2.7
Thickness of cylinder (mm)	3.175
Diameter of cylinder (mm)	114.3
Weight of internal components (g) (5850)	6435
Water density @ 0m (g/cm^3)	1.02813
Length Required for Neutral Buoyancy (m)	0.85
Methane Sensor Exposed Volume (in^3)	18.2
pH/O.R.P. Sensor Exposed Volume (in^3)	28.4
Sensor Volume Equivalent Length (m)	0.234
Minimum Body Length (m)	0.62
Minimum Body Length (in)	24.32

To ensure that buckling will not occur for the MicroFloat design under the load by sea water pressure when submerged at the required depth of 750 m below sea level, buckling calculations were performed. This was done using the worst-case condition of n = 0.25. The calculations are tabulated in Figure 21. The maximum allowable load before buckling will occur is calculated to be 44057 lbf while the maximum load by water pressure is 17623 lbf. This signifies that the MicroFloat design would be able to withstand the load due to water pressure at a depth of 750 m below sea water without buckling with a factor of safety above 1.33.

Table 6. Buckling Calculations

Buckling Calculations	
$F = n\pi^2 E I / L^2$	Al 6061
	Worst Case Scenario
n = end condition	0.25
E = modulus of elasticity (psi)	10000000
L = length of column (in)	48
D = diameter (in)	4.5
t = inner thickness (in)	0.125
I = moment of inertia (in^4)	4.11
Max Allowed Load	44057.08
water pressure @750m	1108.12
Load by water pressure @750m	17623.89
Load Difference	26433.20

MicroFloat is designed to survive static and shear loading at depths of 1000 m. Moreover, the difference in environment between 750 m and 1000 m is used to determine the safety factor, applicable at the depth of 1000 m. According to Britannica, seawater density at a depth of 1000 m is $\rho_{w1000} = 1032.85\ kg \cdot m^{-3}$ [10]. The density of seawater at surface is $\rho_{w0} = 1024.5 \pm 4.5\ kg \cdot m^{-3}$. Assuming that the uncertainty carries by depth, the density of the seawater at the depth of 1000 m is $\rho_w = 1032.85 \pm 4.5\ kg \cdot m^{-3}$. Approximating a linear density profile provides an estimated density at the depth of 750m as $\rho_{w750} = 1030.76 \pm 4.5\ kg \cdot m^3$. The maximum pressure at 1000 m is

$$p = \rho \cdot g \cdot d = 10.1209\ MPa = 1467.91\ psi$$

The maximum pressure at 750 m is

$$p_{750} = 1098.71 \pm 6.20\ psi$$

Therefore, the safety factor is

$$n = \frac{p_{max}}{P_{750,min}} = \frac{1467.91 + 8.27}{1098.71 - 6.2} = 1.35118 \approx 1.35$$

Based on design constraints, the MicroFloat has external diameter $D = 4.5 \pm 0.035\ in$. The uncertainty is standard manufacturing error for dimensions that size platforms such as McMaster-Carr. The rough length is $L = 36\ in$. The dimensions provide volume as follows:

$$V = 572.56 \pm 4.45\ in^3$$

The average density of seawater across the first 1000 m is

$$\bar{\rho} = 1028.68\ kg \cdot m^{-3} = 16.857 g \cdot in^{-3}$$

This is the expected natural buoyancy of the float. As a result, the estimated cumulative mass is given by

$$m = 9651.7 \pm 75.1\ g$$

Based on the design constrains, outer diameter of the cap is $D = 4.5 \pm 0.035\ in$. The thickness consideration can be iteratively adjusted with initial approximation at 1/8 in. Both caps are subject to the same pressure conditions. The top cap, however, has more ruptures for sensors, increasing the stress concentration. The placement of sensors is arbitrary, however, and does not form a well-defined structure to calculate stress concentration. It can be safely assumed that each sensor, because of potting or O-ring sealing, exerts some clamping reinforcement to the top cap, making the stress concentration less than a single, unsupported hole. Moreover, with the largest sensor of diameter 2 in, it is safe to assume that all sensors can be packed in a hole of diameter 3 in. These assumptions now set the design up for a conservative stress concentration estimation by assuming an unsupported hole [11].

By modelling the cap as a 4.5 in disk with a d = 3 in hole in its center, the nominative radial stress and principal stresses can be calculated through a series of calculations as shown:

$$\sigma_\infty = p = 1467.91 \pm 8.27\ psi$$

$$\sigma_{nom} = \sigma_\infty \left(\frac{D}{d}\right) = 2201.87 \pm 52.85\ psi$$

$$\alpha = \frac{d}{D} = \frac{2}{3} \pm 0.00518$$

$$K_t = 3 - 3.14\alpha + 3.667\alpha^2 - 1.527\alpha^3 = 2.084 \pm 0.001$$

$$\sigma_r = K_t \sigma_{nom} = 4588.7 \pm 110.2\ psi$$

$$\sigma_z = p = 1467.91 \pm 8.27\ psi$$

$$\sigma_\theta = 0$$

For cylinder and cap thickness $t = 0.125 \pm 0.007\ in$, the maximum shear is given by the area on cap not supported by the cylinder walls:

$$D_i = D - 2t = 4.25 \pm 0.04\ in$$

$$A_i = \frac{\pi}{4}(D_i)^2 = 14.1863 \pm 0.2428\ in^2$$

$$F_\tau = pA_i = 20824 \pm 375.25\ lb$$

$$A_\tau = \pi D_i t = 1.66897 \pm 0.09455\ in^2$$

$$\tau = \frac{F_\tau}{A_\tau} = 12477 \pm 741.74\ psi$$

Thus, there are 2 principal stresses and 1 shear stress acting on the cap along 3 dimensions. This information can be used to find Von Mises stress on the cap for failure prevention.

$$\sigma' = \sqrt{\frac{(\sigma_r)^2 + (\sigma_z)^2 + (\sigma_z - \sigma_r)^2 + 6\tau^2}{2}} = 21989 \pm 19\, psi$$

Aluminum used has yield strength 35000 psi, so the factor of safety for the cap is

$$n_{cap} = \frac{\sigma_{min}}{\sigma'_{max}} = \frac{35000}{21989 + 19} = 1.5903 \approx 1.59 > 1.35$$

Thus, having 1/8" thick cap with diameter D = 4.5" is sufficient. The rest of the billet not a part of the plate-model of the cap sealing double O-Ring structure and clamping mechanism. The integrity of the cap has been established. Since the thickness of the extruding part of the billet is greater than or equal to that of the cylinder, its integrity can be guaranteed through conservative estimate if the cylinder integrity is promised with the same material: Aluminum 6061. The billet is assumed to withstand all forces through the design consideration of the cap above and the cylinder below:

As an extension from interaction with the cap, the following dimensions are known:

$$D = 4.5 \pm 0.035\, in$$
$$t = 0.125 \pm 0.007\, in$$
$$D_i = 4.25 \pm 0.0364\, in$$

The body of the float can be treated as a pressurized cylinder. The tangential and radial stress magnitudes are identical for a cylinder pressurized from the inside or outside. Clamping screws are assumed to not cause stress concentrations. The longitudinal stress is calculated based on force balance on the cap as shown

$$\sigma_l = p\frac{D^2}{D^2 - D_i^2} = 13588.7 \pm 121.9\, psi$$

The pressure difference between the inside and outside is less than the pressure outside. Since the tangential and radial stresses scale with pressure gradient, a conservative simplification would be to assume zero internal pressure. The magnitudes of maximum radial and tangential stresses occurring on the inner surface are therefore given as follows:

$$\sigma_t = \frac{D_i^2 p}{D^2 - D_i^2}\left(1 + \frac{D^2}{D_i^2}\right) = \frac{D^2 + D_i^2}{D^2 - D_i^2} p = 25709 \pm 239\, psi$$
$$\sigma_r = \frac{D_i^2 p}{D^2 - D_i^2}\left(1 - \frac{D^2}{D_i^2}\right) = p = 1467.91 \pm 8.27\, psi$$

As established before, the cylindrical component faces negligible shear stress. From the principal stresses established above, the von Mises Stress for failure can be found.

$$\sigma' = \frac{1}{\sqrt{2}}\sqrt{(\sigma_l - \sigma_r)^2 + (\sigma_l - \sigma_t)^2 + (\sigma_r - \sigma_t)^2} = 20993 \pm 207\, psi$$

The factor of safety for the cylinder is

$$n = \frac{\sigma_{min}}{\sigma'_{max}} = \frac{35000}{20993 + 207} = 1.65093 \approx 1.65 > 1.35$$

Aluminum 6061 with 1/8 inch thickness for cap, billet, and cylinder, provides a versatile, resilient, and structurally sound solution to the problem at hand. Minor changes in design greatly influence buoyancy. However, most configurations are expected to limit the length to less than 3 feet.

Finally, the MicroFloat should be able to withstand many cycles of diving to the full depth of 750 m and resurfacing without suffering from fatigue. For this portion of the analysis, the cylindrical body made from Al 6061-T6 is examined assuming a triaxial state of stress along the longitudinal, radial, and tangential axes as illustrated in the stress analysis above. The tensile yield strength of Al 6061 is 276 MPa and the tensile ultimate strength of Al 6061 is 310 MPa. [11] Aluminum alloys generally do not exhibit endurance limits, so fatigue strength for varying numbers of cycles is seen from an experimentally determined S-N diagram for a standard rotating specimen. [12] The material exhibits a fatigue strength of approximately 32 ksi (220.6 MPa) at 10^5 cycles and approximately 37 ksi at 3×10^4 cycles. [12] Marin factors are applied to translate the experimental fatigue strength $S_f{}'$, which is valid only for the particular rotating specimen used, into the fully corrected fatigue strength S_f that can apply to all fully reversed loading for a much more general class of geometry encompassing all non-beam elements such as the MicroFloat body. The calculated Marin factors and their significance are given in Table 7. A more detailed calculation is provided in Appendix A.

Table 7. Marin Factors to Correct Fatigue Strength

Factor	**Correction Significance**	**Value**
k_a	Surface finish and quality	0.9862
k_b	Size and rotation/lack of rotation	0.8325
k_c	Loading (bending, axial, and torsional)	0.8500
k_d	Temperature	1
k_e	Reliability; decrease strength to increase percentage of samples that will reach desired life	0.8140
k_f	Miscellaneous; corrosion, plating, cycle frequency, etc.	0.7500

The corrected fatigue strength is calculated as $S_f = k_a k_b k_c k_d k_e k_f \cdot S_f{}' = 93.98\, MPa$ at 10^5 cycles and $108.70\, MPa$ at 3×10^4 cycles. The minimum pressure applied to the MicroFloat is atmospheric, $p_{atm} = 0.1013\, MPa$, while the maximum pressure is $p_{max} = 1098.7\, psi = 7.58\, MPa$. This maximum corresponds to the hydrostatic water pressure at a depth of 750 meters. To ensure adequate overheard in the strength of the design, the analysis will instead use the hydrostatic water pressure at a depth of 1000 meters, $p_{max} = 1467.9\, psi = 10.1\, MPa$. The corresponding von Mises stresses, which take into account the combined effects of normal and shear stresses applied simultaneously, at sea level and at 1000 meters were calculated as $\sigma_0{}' = 1.45\, MPa$ and $\sigma_{1000}{}' = 144.7\, MPa$, respectively. These minimum and maximum values lead to a midrange stress of $\sigma_m{}' = 73.08\, MPa$ and a stress amplitude of $\sigma_a{}' = 71.63\, MPa$. The midrange stress and stress amplitude are used to characterize non-periodic, non-fully-reversed loading, which the MicroFloat will experience any time its mission deviates from a continuous dive to maximum depth followed by a continuous ascent to the surface, and are adequate for a fatigue analysis. With these characteristic stresses, and assuming a life of 3×10^4 cycles, the modified Goodman failure criterion shows a 1.12 factor of safety against fatigue. This is verified with the ASME elliptic failure criterion, which shows a higher 1.40 factor of safety against fatigue. A yield check reveals that the design shows a 1.90 factor of safety against yielding due to the cyclic loading. Any higher number of cycles resulted in unacceptable factors of safety, so 3×10^4 cycles represent the upper limit of what this design can withstand. The failure criteria are described in greater detail in the appendix.

These results illustrate that the design is safe for 30,000 cycles of diving from sea level to maximum depth of 1000 meters, which is likely to far exceed the scope of any study for which the MicroFloat may be deployed. This fulfills the required depth range of 750 meters and gives the ocean scientists the ability to map deeper into the ocean if desired without worry of fatigue failure.

A buoyancy test was conducted with the prototype to verify the center of mass and buoyancy calculations. This was conducted at the acoustic water tank at Georgia Tech with the kind support of Dr. Francois Guillot. The prototype was able to stay buoyant at the surface with the top cap of the MicroFloat's volume being above water level.

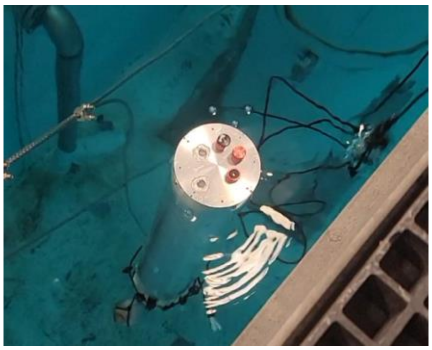

Figure 21. MicroFloat prototype with positive buoyancy at the water's surface.

This signifies that the MicroFloat design has sufficient buoyancy to support weight of the necessary sensors that were not available. The MicroFloat is also able to float upright in the water when extra weights were added to simulate the weight of the missing components. The center of mass of the MicroFloat is below its centroid and therefore will not encounter stability issues during its deployment.

10. Final Design, Mockup and Prototype

The detailed design for the MicroFloat is divided into three sections: the external design of the vessel, the internal design structure for supporting the electronics and hardware, and ultimately the electrical design that controls the MicroFloat. As the design needs to be able to withstand pressures at up to 750m of water and maintain a watertight seal, the CAD was made in tandem with the engineering analysis done by the team. Buoyancy and volume need to be maximized within the overall size constraints of the MicroFloat, while weight needs to be minimized. The in-depth mechanical and electrical analysis is performed and explained in section 9 of the report, but the results from that section informed all critical aspects and dimensions of the external CAD design.

For the body of the MicroFloat, the team identified a suitable Al 6061 pipe that satisfies the strength and geometry requirements from the pressure calculations. The pipe is sealed at both ends by a set of machined caps that employ a double O-ring seal that will provide adequate and redundant sealing at maximum pressure. These caps are secured axially and radially by two set screws that thread through the upper and lower pipe wall. Additionally, the upper cap provides mounting space for the communication and sensing hardware of the MicroFloat. All connections from the sensors and other components (LED flasher, antenna, and GPS), are routed through sealed bulkhead connectors that supply a waterproof electrical passthrough to the internal electronics. This cap also possesses an external on/off switch for external control and an air vent for depressurizing upon resurfacing. All of these components are then encompassed by two handles that provide a hooking point for retrieval along with protection for the main sensors. The handles will also prove useful when separating the top cap from the cylinder body when performing maintenance or disassembly. The bottom cap of the MicroFloat contains the bellows assembly and is dedicated to ensuring a hydraulic seal between the external bellows and the internal oil pumping system. On the inner face of the cap, there is a 0.5” FNPT tapped hole so standard hydraulic fittings can be used. The outer face of the cap has mounting holes and an O-ring, so that the rubber oil bladder can be clamped and sealed to prevent oil leakage to the surrounding water. To prevent damage to the oil-bladder, an additional cage is mounted to the bottom cap to ensure the bladder’s safety during handling or operation. Lastly, each of these machined caps include inward facing tapped holes for mounting the internal hardware. The top and bottom Cap Assemblies can be viewed below in Figure 22.

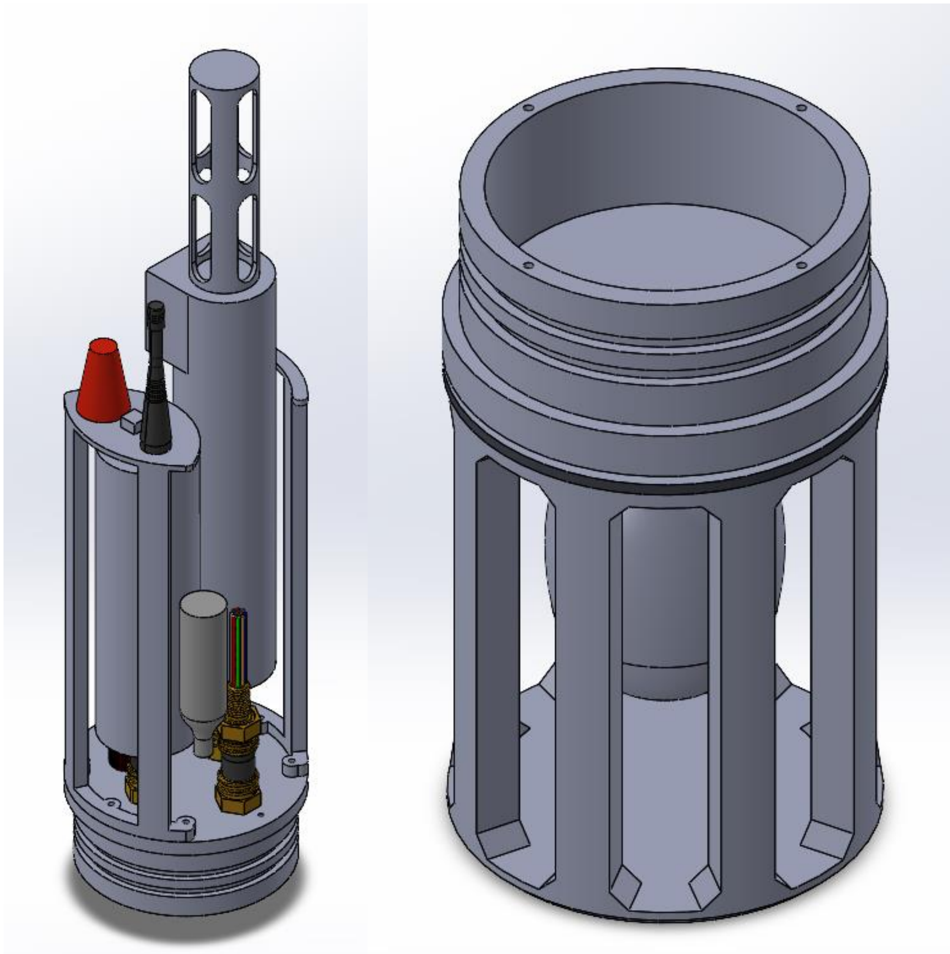

Figure 22a/b. Top cap assembly / Bottom cap assembly.

For the internal body of the MicroFloat, the team decided to design a 3D printed framework that would house all internal parts. The internal framework is divided into two parts, the top frame and bottom frame. The top frame is connected to the top cap by four M3 screws, and the bottom frame is connected to the bottom cap using four M3 screws as well. The top frame will serve as the housing for the PCB and motor controller. The top frame has cutouts located on the side to allow for wires to route easily between the PCB and the remainder of the system. The bottom frame consists of five connected housings. The team chose to split the bottom frame into five independent parts to allow for easier repair. These housings hold the battery, reservoir, and the hardware for the bellows system. Each layer of the housing is connected using four M3 screws. These screws ensure that the internal frame will not fall apart when they are removed from the MicroFloat. The battery is secured within its housing by a mount that extends from the inside bottom face of the frame. The motor will be mounted onto a motor plate that is located within its housing. This will ensure that the torque from the motor does not destroy its housing as 3D printed components are prone to powdering under repeated stress. The pump is mounted onto its housing using a custom fabricated aluminum mounting bracket. This bracket also mounts into the motor plate to give the design more strength.

The bracket is custom fabricated due to there not being an off the shelf option that meets the design specifications for this design. The reservoir tank is made of a 3” diameter by 5” long PVC pipe with two 3” endcaps. Additionally, there is a 0.5” FNPT tapped hole located in the bottom of the tank to allow for a standard hydraulic fitting to be used. The team chose to use PVC for the reservoir due to its low weight and cost when compared to a 3D printed custom reservoir. Slots were added into the sides of the internal housings to allow for wires to pass through. A separate passthrough was created to allow for the tube to connect the reservoir to the pump (Figure 23).

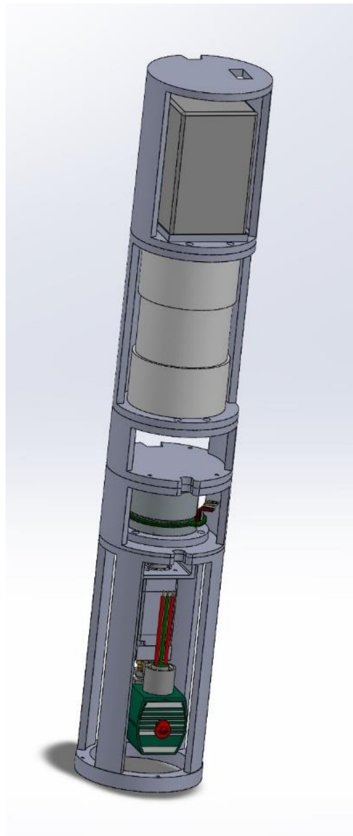

Figure 23a. Bottom internal frame assembly, showing from top to bottom the battery, oil reservoir, tube passthrough, oil pump motor, oil pump, and solenoid. Hydraulic lines are not shown.

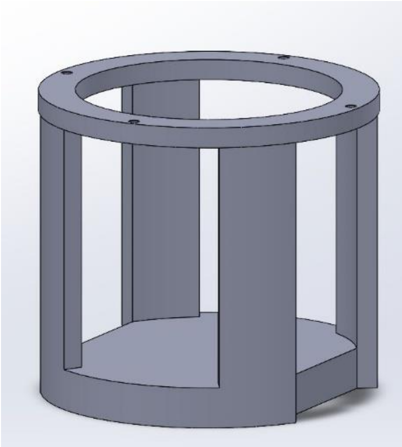

Figure 23b. Top internal frame without PCBs, designed to be modular and easily removable.

A complete prototype of the vehicle was assembled from machined, 3D-printed, and stock parts as shown below in Figure 24. This functional prototype was water tested at Georgia Tech.

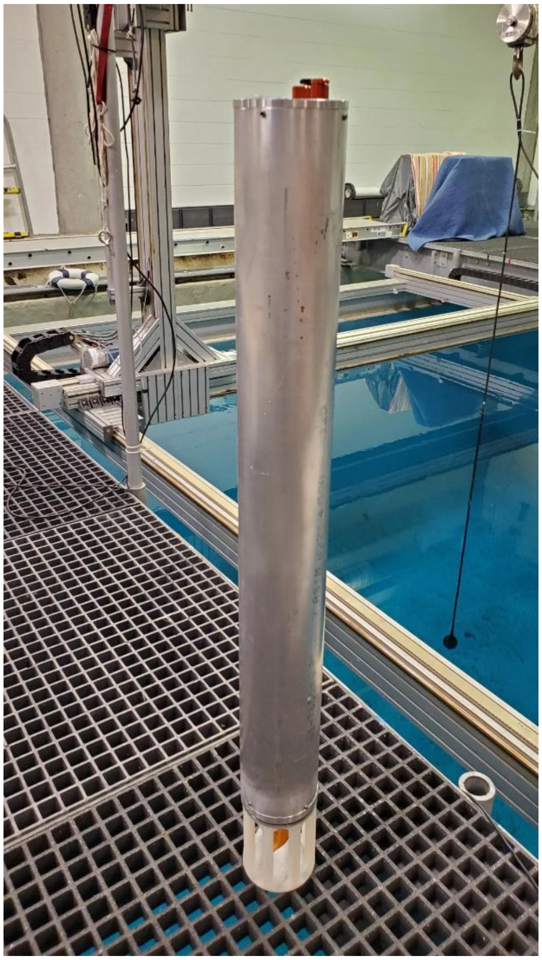

Figure 24. Fully assembled prototype at Georgia Tech's acoustic water tank, ready for testing.

The electrical design utilized a lot of small and affordable parts to fit into the MicroFloat and be easily/inexpensive to replace in case of water leakage. The MicroFloat is being controlled by the Teensy 4.1 microcontroller which was chosen because of its size, cheap cost, abundance of pins as shown in Figure 25 and a built in SD card reader to store data its gathered. The microcontroller utilized a N-channel power MOSFET to get power from the battery without short-circuiting the chip. The system was originally going to run a state machine code that utilizes the BlueRobotics 30Bar Pressure Senor to check if the floats current depth is in the desired error margin. If the depth is too low the DECS 50/5 (Digital EC Controller Sensorless) Maxon motor control is set to counterclockwise which fills the bellow driving it up and vice versa. Due to timing and issues with the pressure sensor the float was tested with a simple code that expand and contracted the bellows on a timer. Outside of motion the design implements other features that will be used in the final product, but on a smaller scale. A NEO-6m GPS Module and Adafruit RFM69HCW for GPS Tracking and radio transmitting, these signals are extremely weak for what will be needed in the ocean but useful for testing program logic. The code for these systems compiled fine but the previously stated issues prevented further testing.

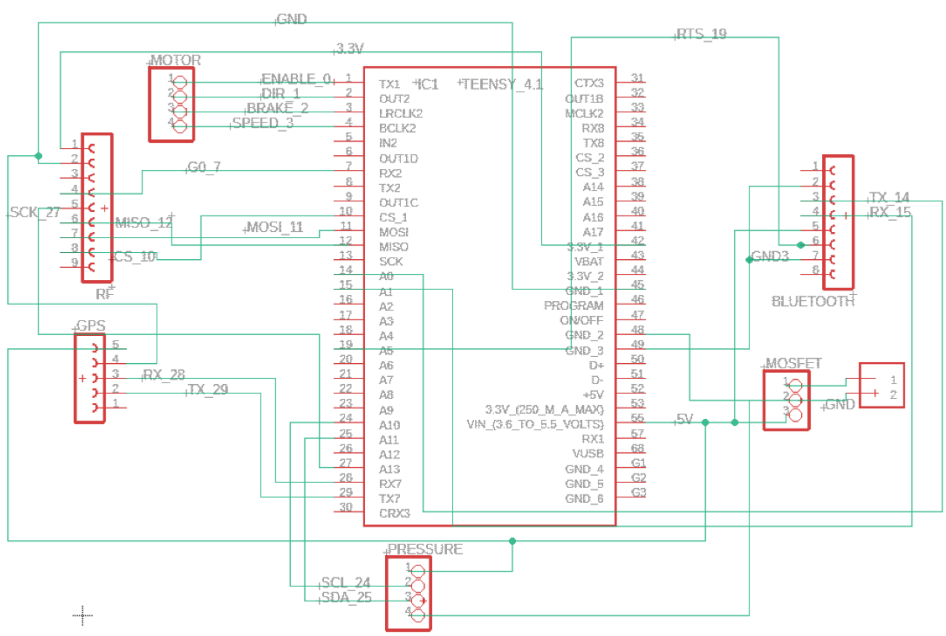

Figure 25. Electrical system PCB schematic.

11. Manufacturing

The MicroFloat was designed with the ease of manufacturability and assembly in mind. Careful consideration was given to the modeling of each part to ensure the feasibility of mass manufacturing. This is because the MicroFloat must be deployed in swarms to achieve its intended purpose, thus it the whole design should be easily mass produced. This means that the individual components should not require specialized machinery and must be easily manufactured efficiently though automated processes is possible. Keeping this in mind, off the shelve parts were utilized whenever possible and carful design choices were made.

The main body of the MicroFloat designed to be made of anodized Al 6061. The diameter of it is a standard tube size of 4.5-inch outer diameter with a wall thickness of 1/8 inch. This allows for the outer shell to be directly sourced as anodized or un-anodized aluminum tube cut to specific length. This saves on the cost and need to manufacture a custom-made shell. The 2 end caps of the tubes are specifically designed to fit the bellow and sensors thus cannot be purchased directly as off the shelve parts. However, they are both designed to be a single piece and can be manufacturable with a single fixture on a CNC machine. This simplifies the manufacturing process and eliminates the possibility of misalignments due to changing of fixtures during the machining process. It being designed to be made of Al-6061 too is also a conscious decision to reduce machining time during mass manufacture and eliminates the need for specialized machineries.

The internal rack and the bellow cage of the prototype is currently manufactured by 3D printing using ABS plastics. However, the internal racks are designed to be manufacturable by standoffs, and aluminum plates. The standoffs are off the shelve parts while the aluminum plates can be machined to the design by using a water jet. The extra weights are accounted for in the design calculation while this arrangement will also more structurally rigid and able to support heavier internal sub-assembly. This also has the added benefit of achieving a lower cost compared to 3D printed parts. The bellow cage can still be 3D printed in mass production. However, it should be made out of strong materials such as PLA or carbon fiber. This is because it must be able to support the whole weight of the MicroFloat while also strong enough to withstand impact. The bellow cage is an essential component to protect the bellow from ruptures.

The internal electronics is currently prototyped using a breadboard and an Arduino. However, in mass production, it is designed be manufactured as a single piece of PCB with embedded microcontroller and motor driver. The electric diagram for such has already be drawn but the PCB layout have yet to be completed. Using a single piece of PCB eliminated the need for connecting wires, significantly lowering the possibility of loose connections. The custom PCB boards also increases the ease of manufacture and decreases the time needed to connect all the components. Other electronic components such as the battery, motor, pump and sensors will all be off-the-shelve parts in order to save time and cost manufacturing them while also ensuring reliability of the whole MicroFloat.

12. Societal, Environmental and Sustainability Considerations

Societal, environmental and sustainability impact were taken into consideration while designing our product. This is especially important as the MicroFloat will be operated in the ocean where it may potentially come across regions with great but delicate biodiversity.

The MicroFloat is designed to have an anodized 6061 aluminum outer shell that is watertight. Choosing anodized aluminum 6061 ensures that our design will not introduce heavy metals into the sea water while decreasing the chance of corrosion. The guidelines given in ASTM G52 – 20 is closely followed in evaluating corrosion and marine fouling behavior of materials exposed to a saltwater environment. At the same time, the designated anodization process will produce a hard, corrosion resistance layer on top of the 6061 aluminum. This layer ensures that the aluminum outer shell does not undergo corrosion in sea water which may result in internal components or chemicals being exposed to sea water. The anodized outer shell also avoids the use of antifouling paint. Antifouling paint is often used by marine vessels to control the growth of marine organisms on their hull. However, they can cause harm to other marine organisms. The anodized layer itself is sufficient to reduce the growth of marine organisms for our required mission timeframe of 2 weeks due to it being a ceramic layer

The MicroFloat design has a fatigue life cycle of over 30,000 cycles. This means that the outer shell can sustain more than 30,000 dive cycles (pressurized and depressurized) before there is even a possibility of fatigue failure. The design of the MicroFloat is also modular with universal connectors and adaptors for different sensors or add-on devices. The modularity of the design allows for components within the MicroFloat to be easily taken out and exchanged or upgraded depending on the mission requirements. This ensures that if maintained properly, the MicroFloat can be used for a life span of over 8 years. Together with the choice of not using any disposable or one-time components in the MicroFloat assembly, the amount of waste generated can be reduced. This is especially important when the MicroFloat is deployed as a swarm, ensuring that the metal trash produced is minimized while reducing wastage of both materials and energy.

All together the measures and considerations taken into account when designing the outer shell of the MicroFloat and the choice of materials prevent any harmful substance from released into the sea water that may potentially affect the local marine life, reducing the potential of environmental impact and ensuring the local fish stock will not be affected. While the assembly takes into account repairability ease of modification, reducing the potential amount of waste produced.

The design of the hydraulic system within the MicroFloat takes the guidelines given by ASTM F2798-09 into consideration. The pipes and pipe fitting were designed to withstand the working pressure with a factor of safety above 5 in all cases while avoiding having any elements exposed directly to sea water. This ensures that the hydraulic system of the MicroFloat will not leak and does not pose a potential threat to marine life.

Furthermore, all the electrical components used are RoHS compliant ensuring that they pose little to no threat of releasing heavy metals into the environment. This also ensures that our product does not pose a potential danger to operators or anyone maintaining it. The battery for the MicroFloat is located within its own rigid compartment. This reduces the risk of puncturing or compression of the battery which can potentially lead to a spontaneous combustion.

Thoughtful considerations were taken when designing the MicroFloat to ensure that the societal and environmental impacts are minimized while taking into account the sustainability of the design. These design considerations and processes should be continued as the design is modified and the prototype is built.

13. Risk Assessment, Safety and Liability

In general, the risks associated with the normal operation of the MicroFloat are low but must be considered. These risks stem primarily from failure of any of the vehicle's subsystems while it is deployed, with the threat largely existing to the marine environment it is surveying. However, there are also risks for the operator involved in the proper assembly and maintenance of the MicroFloat. Safe operation and deployment were of utmost importance during the design of the MicroFloat and possible risks and failure modes were analyzed. A risk assessment matrix is presented in Appendix B with a summary of potential risks in the assembly and deployment of the MicroFloat and associated design choices intended to mitigate or minimize those risks.

Environmental risks are any risks associated with the vehicle causing damage or harm to its surroundings. Mechanical failures, such shell stress failure, bladder rupture, and sealing failure, fall under this category, since many of these failures are catastrophic for the MicroFloat and render it at best unable to return to the surface (and likely will cause it to sink as lost debris and/or spill its oil out into the open ocean, polluting the waters and adversely affecting marine life). Detailed engineering analyses including stress, fatigue, and buckling, which are described earlier in this document, have been carried out with the intention of ensuring that the MicroFloat's primary structural members have significant overhead in strength to resist any abnormal or unexpected loading during a mission. The oil bladder, which is now a small fraction of what a custom oil bellows costs, is constructed from seamless rubber designed to withstand repeated physical abuse in a gym environment, minimizing its chances of splitting open or rupturing from oil pressure. The oil reservoir's volume is also designed to be at most equal to the volume of the fully expanded bladder so that the bladder can never be overfilled. It is also ensconced in a protective cage to prevent any physical impacts in the water from compromising the bladder. The bladder should be visually inspected for damage after every retrieval, and should it ever need to be replaced, it can be readily found online for the price of a small lunch.

Electrical failures are also possible. Without any practical way of cooling integrated circuits or the PCBs inside a sealed pressure vessel, the microcontroller and its ancillaries may overheat if they are run at high performance for an extended period of time, potentially even burning the PCB in the most extreme cases. Therefore, the design is intended to use as little power as possible, only running the buoyancy engine and microcontroller for data collection in controlled bursts, leaving ample time between runs to lower die temperature via passive convection inside the cylinder. The battery itself can also present multiple risks to the operation and health of the vehicle. The first, less severe risk arises from the vehicle fully depleting its battery while deployed, either due to battery degradation over time or low remaining charge upon deployment due to the operator's failure to recharge the unit. In either case, the battery is well-equipped with substantially more capacity than it should need to fulfill its mission time of two weeks so that it effectively has overhead in power in case an operator forgets or is unable to recharge during routine maintenance. The second, more severe risk is of total battery failure whereby the battery chemically fails and becomes unusable. This poses a threat both to the internal components of the MicroFloat as well as to the ocean and surrounding marine life, particularly if the battery leaks or bursts. To mitigate this risk, routine battery health checks are recommended during normal out-of-water maintenance to ensure there is no physical damage to the battery and that it continues to charge to the appropriate voltage levels.

A complete failure modes and effects analysis (FMEA) is included and detailed in Appendix C. Future revisions of the MicroFloat may include fault monitoring and detection capabilities, potentially in the form of water or humidity sensors for checking for water ingression or temperature sensors to put the vehicle in an effective limp mode if electronics get too hot. A dedicated battery controller may also be added to the electronics package for more reliable and convenient battery health monitoring. Such improvements will hone the fault detection and corrective capabilities of the MicroFloat, ultimately making it a more robust and reliable system while simultaneously reducing the risk of contaminating the surrounding ocean or sinking to the ocean floor.

14. Patent Claims and Commercialization

The MicroFloat remains part of an ongoing effort by Dr. Michael West and his research group at Georgia Tech and will continue to be developed there at the conclusion of the Swarmers’ efforts. At present, there are no plans to make patent claims or commercialize the vehicle, as its functional scope is very narrow and it operates primarily on the already well-established oil-driven buoyancy engine design. At the height of the larger research study at hand, hundreds of MicroFloats or even more may be deployed as a swarm, but even this large-scale operation will remain confined to the context of the research study in the hands of the ocean researchers and Dr. West. Further down the line, an optimized design could be commercialized and brought to the data collection float market as a low-cost, compact alternative if so desired.

15. Team Member Contributions

Table 8. Group Role Assignments and Descriptions

Role	Group Member	Description
Project Manager	Alexander Olsen (ME)	Coordinates group meetings and scheduling; ensures all deliverables are completed on time; ensures project timeline is maintained
Controls and Fabrication Lead	Dahrius Abdelnur (ME)	Ensured manufacturability and viability of all designed components; works with electrical lead to develop electronic control system
CAD and Sourcing Lead	Joseph (Will) Jarman (ME)	Manages project CAD and computer-aided analysis like FEA; represents the team in supplier communications
Electrical Lead	Sidney Wise (CmpE)	Manages electronics and communications systems; responsible for developing electronics BOM and determining feasibility
Mechanical Lead Financial Manager	Terence Lui (ME)	Ensures that design meets engineering specifications; develops mechanical assembly
Software and Web Development Lead	Vatsal Trivedi (ME)	Responsible for developing project website; works with electrical lead when necessary, and ensures structural integrity

Alex Olsen continued to help organize the schedule, and he made sure ownership is assigned for all components of the project. He also provided weekly updates to stakeholders, and he worked on engineering analysis. He oversaw the development of the expo poster, participated in the acting of the expo video, and served as primary editor for this document. Dahrius Abdelnur oversaw the team’s manufacturing and fabrication timeline and helped machine and assemble parts of the MicroFloat. He also helped with wiring and troubleshooting the electronics. He loaned the team many of his personal tools and equipment. He also directed the expo video production and handled video editing and served as primary editor for this document. Joseph Jarman modelled the internal components and assembly of the MicroFloat, concentrated on how to achieve water tightness at high pressure, finished the fabrication package, and helped write the weekly emails. He also played an integral role in obtaining components from brick-and-mortar stores when necessary. Sidney Wise constructed the circuit diagram and TinkerCAD simulation for the electrical subsystems and controls as well as conducted power analysis on the electrical components. She also purchased the electrical components and assembled the prototype of the electronics unit. Terence Lui performed engineering analysis on the mechanical design, worked on environmental considerations, handled the BOM for budget and weight calculations, and helped with sourcing the required materials and components. He also helped to develop and record the audio for the presentation segment of the expo video.

Vatsal Trivedi conducted engineering analysis on mechanical design for static and dynamic loading, identifying possible stress concentration and modes of failure. He also purchased the mechanical components, helped Terence to develop and record the audio for the presentation segment of the expo video, and developed the final website

16. Conclusions, Future Work, and Project Deliverables

The team has followed the schedule shown below in the Gantt chart in Figure 26. It serves as a guide to the milestones achieved along the way in the team's progression through the project, as well as a roadmap to ensure that all deliverable dates were met.

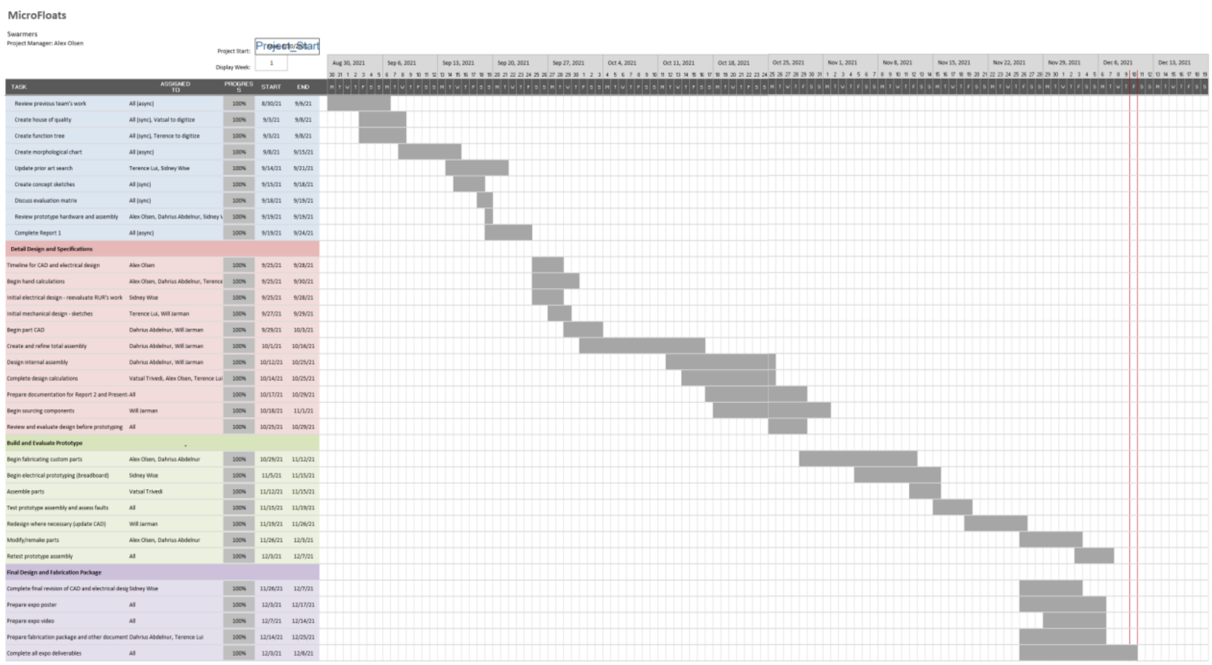

Figure 26. Completed Gantt chart showing the team's progression on the project.

The team's main advisors are Dr. Jariwala, the ME advisor, and Dr. West, the ECE advisor and sponsor. The team communicates on a weekly basis with Dr. West. This is achieved by having weekly one-hour meetings. During these meetings a weekly presentation is put together. Through this medium, the team's progress, questions, deliverables, and problems are discussed. Before this meeting, the team constructs a weekly email that is sent to both Dr. West and Dr. Jariwala. This email contains the weekly deliverables unless a different due date has been previously discussed.

The major tests undertaken to validate the prototype involve buoyancy engine function, specific density at deployment, and water-tightness. The buoyancy engine functions as expected, expanding and contracting the bladder as a response to the input from microcontroller. The connections between all components is airtight, and no leaks are found which might need future caution. Moreover, the connection between the bottom cap and the bladder, characterized by an O-Ring and an NPT fitting, is also resistant to leakage. Buoyancy engine can therefore be replicated as it is.

The acoustic water tank at Georgia Tech was used to perform the buoyancy and watertightness tests. When introduced to the water, the prototype was lacking the sensors. Therefore, additional weight equivalent to the expected weight from sensors was added to the cylinder using steel scrap. The prototype maintains neutral buoyancy and stable vertical composure at a mass slightly higher than the expected addition of sensors. It is therefore, a practical prototype which can stay afloat, thereby validating the principle of vertical motion through volume alteration. When originally tested without complete mass and pressure, both caps were completely watertight. However, when the final assembly was introduced to the water, that was not the case and leaks were detected. While this flaw requires further investigation, there are two probable causes which are driving factors.

The most important explanation for the failure was the use of non-anodized aluminum and the compression mechanism used. The bolts hold the cap together by pressing down on the soft cylinder. Therefore, any slight over-torquing easily deforms the cylinder, making it out of round. The team attributes the post-assembly leakage to the formation of new cavity as a result of imperfect mating between the cylinder and the O-Ring caused by one of the bolts meant to hold the cylinder in place. Another explanation not directly applicable but worth noting is the performance of O-Rings under pressure. While the maximum depth of the pool was 20 feet, future prototypes require testing in high-pressure environments to replicate oceanic conditions to confirm the functioning of the O-Rings.

Besides the water breach due to deformation during assembly, there are no issues found in the prototype. Anodization prior to assembly, redesign of clamping mechanism to eliminate compression, as well as clear set of instructions to prevent the repetition of the deformation can easily address the concern. In addition, reforms related to mass manufacturing, adaptations based on high pressure testing, and modification of electrical components and microcontroller algorithms based on navigation-based progress are essential next steps to make a more complete and versatile prototype. Some design aspects to consider for the next prototype which were not addressed for the current capstone design project based on requirements also include underwater signal transmission and mapping algorithm.

As the team proceeds to conclude the project as anticipated by the timeline, it has laid out hand-over documentation to thoroughly summarize the design and the future work necessary, so the progress made so far can be used as a basis for future improvements like better failure detection and correction. The success of the buoyancy engine, the modularity of the sensors and the flexibility of the internal housing, and the validated design calculations are valuable takeaways from the effort. The team hopes that the prototype will continue to be developed and tested, taking steps towards full-scale deployment in the Gulf of Mexico and ultimately uncovering the mystery behind the methane plumes on Enceladus.

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Appendix A: Marin Factor Calculations

$k_a = a \cdot S_{ult}^b$, where a and b depend on the surface finish

For drawn or machined metals, $a = 4.51$ and $b = -0.265$ [13]

$k_b = \left(\frac{d_{eq}}{0.3}\right)^{-0.107}$, where $d_{eq} = 0.370d$ for a hollow tube (equivalent diameter) [13]

$k_c = 0.85$ for pure bending loads [13]

$k_d = 1$ except at high temperatures, which are not observed in the MicroFloat's operating environment [13]

$k_e = 0.814$ for 99% of samples to reach their expected life [13]

$k_f = 0.75$ conservatively to account for continual subjection to corrosive oceanic environment

In general, the miscellaneous factor k_f is difficult to obtain values for, as it is extremely application dependent. A reasonable value of 0.75 is assumed here to account for the corrosive oceanic environment (even though the final design with be made of anodized aluminum with high corrosion resistance) as a conservative estimate of a 25% reduction in fatigue strength purely as a result of corrosion, which is not accounted for in the other correction factors.

Failure Criteria:

$$Yield: \frac{\sigma_a{}'}{S_y} + \frac{\sigma_m{}'}{S_y} = \frac{1}{n}$$

where $\sigma_a{}'$ is the von Mises stress amplitude, $\sigma_m{}'$ is the von Mises midrange stress, S_y is the tensile yield strength, and n is the factor of safety [13]

$$Modified\ Goodman: \frac{\sigma_a{}'}{S_f} + \frac{\sigma_m{}'}{S_{ult}} = \frac{1}{n}$$

where $\sigma_a{}'$ is the von Mises stress amplitude, $\sigma_m{}'$ is the von Mises midrange stress, S_f is the fully corrected fatigue strength at a specified number of cycles, S_{ult} is the ultimate tensile strength, and n is the factor of safety [13]

$$ASME\ Elliptic: \left(\frac{\sigma_a{}'}{S_f}\right)^2 + \left(\frac{\sigma_m{}'}{S_y}\right)^2 = \frac{1}{n^2}$$

where $\sigma_a{}'$ is the von Mises stress amplitude, $\sigma_m{}'$ is the von Mises midrange stress, S_f is the fully corrected fatigue strength at a specified number of cycles, S_y is the tensile yield strength, and n is the factor of safety [13]

Appendix B: Risk Assessment Matrix

Table 9. Risk Assessment, Evaluation, and Mitigation

No.	Risk	Frequency	Severity	Initial Risk Level	Mitigation	Final Risk Level
1	Hydraulic oil bladder rupture	D	2	Medium	Protective cage around bladder, oil reservoir with full capacity not exceeding bladder volume, seamless bladder construction	Low
2	Shell failure due to pressure	D	1	High	Extensive engineering analysis with generous factors of safety (85% overhead), designed to survive at depths significantly greater than operating	Low
3	Shell failure due to fatigue	D	1	High	Use of durable 6061 aluminum; pessimistic loading conditions assumed during analysis	Low
4	Shell failure due to buckling	D	1	High	1/8" wall thickness to ensure high stiffness in compression	Low
5	Water intrusion	C	2	High	Detailed O-ring groove design per manufacturer's recommendations, high endcap manufacturing tolerance, roundness requirement for shell, durable internals resistant to small amounts of water	Medium
6	Internal oil leak	C	3	Medium	Uprated fittings and lines (in excess of thousands of psi), sealed and leak-tested oil reservoir	Low

7	Danger to assemblers from oil	B	3	Medium	Biodegradable, nontoxic oil specified by the design	Low
8	Micropump failure	D	2	Medium	Micropump sourced from reputable pump manufacturer, extensive buoyancy engine testing and validation	Low
9	Motor failure	D	2	Medium	Integrated and dedicated motor controller, control algorithm designed to work well within operating limits	Low
10	Electrical short during assembly	C	2	High	Full custom PCB potentially with resin coating, tight and strong mechanical wire connections	Medium
11	Loss of battery charge	B	2	High	Very high capacity battery specified (6 Ah) for power requirements; could run well beyond rated run time in emergency situations, easily accessible connections for easy charging	Medium
12	Battery failure	D	1	High	Considerable protections against water intrusion, may specify custom voltage and current controller to prevent overcharging, enough built-in capacity to avoid total depletion during normal use	Low

Legend:

Frequency of Exposure	**Severity**			
	1: Catastrophic	2: Critical	3: Marginal	4: Negligible
A: Frequent	A1	A2	A3	A4
B: Probable	B1	B2	B3	B4
C: Occasional	C1	C2	C3	C4
D: Remote	D1	D2	D3	D4

Risk Level	High	Medium	Low

The risk assessment analysis framework is adapted from [14].

Appendix C: Failure Modes and Effects Analysis (FMEA)

Table 10. FMEA

	Failure			Cause		Detection		Action	
Item	Potential Failure Modes	Potential Effect of Failure	Severity	Potential Cause	Occurrence	Design Control	Detection	Risk Priority Number	Action
Shell	Yield and loss of integrity	Unit failure and disintegration, ocean pollution and contamination	10	Stress due to pressure, stress due to fatigue	2	Designed with considerable overhead for a sufficient FOS; no detection measures in place	10	200	Sourcing high-quality aluminum during manufacture
Shell	Buckling and loss of shape and integrity	Unit failure and disintegration, ocean pollution and contamination	10	Lack of stiffness in tube design	2	1/8” wall thickness in tube for increased stiffness; no detection measures in place	10	200	Sourcing high-quality aluminum during manufacture
Bladder	Rupture	Loss of ability to resurface, ocean contamination	9	Puncture by foreign object, overfilling with oil	3	Seamless bladder design, oil reservoir with capacity less than or equal to bladder volume, protective cage; can also add oil level sensor	6	162	Regular inspection of bladder for cracks or tears, regular above-water test of proper functionality
O-Ring Seals	Cracking and loss of elasticity	Water intrusion; interference with electronics, fouling of mechanical components	8	Excessive temperature cycling leading to brittleness	5	Operation is limited to ocean temperature gradients; more careful consideration before Arctic or Antarctic deployment	10	400	Iterate design before deploying in excessively cold environment s
O-Ring Seals	Loss of watertigh tness	Water intrusion; interference with electronics, fouling of mechanical components	8	Incorrect fitment in grooves; manufacturing defect in endcap or tube	3	Grooves designed according to manufacturer’ s recommendati ons; tight but realistic tolerances	10	240	Regularly inspect unit for water intrusion or leaks; replace O-rings if necessary

						built into parts			
Battery	Loss of charge	Loss of ability to complete mission, loss at sea	9	Total depletion during mission, operator failure to recharge at appropriate intervals	4	Intended to have much more life than is necessary for a single deployment; can implement battery depletion protection	5	180	Recharge battery upon each successful recapture and evaluate health
Battery	Explosion/chemical failure	Unit failure, potential internal corrosion, and ocean contamination	10	Unintended battery degradation over many 0%-100%-0% cycles, manufacturing defect	2	Intended to have much more life than is necessary for a single deployment; can add dedicated battery controller	6	120	Charge in the range of 15%-85%-15%; regularly inspect for bulging or damage
Internal Housing	Fracture	Loss of internal structural rigidity and mechanical support	6	Excessive force applied in unit disassembly for maintenance	6	Components 3D printed from strong ABS with reasonable infill for sufficient strength	10	360	Handle internal housing components with care during disassembly
Mounted Sensors	Loss of data collection	Mission failure and node loss in 3D spatial map	4	Manufacturing defect, water intrusion, improper electrical connection	2	Secure bulkhead connectors specified in design, desired sensors are commercially rated for conditions far beyond what is required here	4	32	Regularly test sensors and verify collected/transmitted data for accuracy
Microcontroller	Overheating	Potential loss of control over components depending on built-in protections, burnt IC and/or PCB	6	Lack of practical cooling solutions inside a sealed pressure vessel	4	Microcontroller operates intermittently only when required to reduce power usage	4	96	Test limits of microcontroller for extended period above water and measure temperature, ensure mission duration falls within this limit
Micropump	Loss of pumping	Potential loss of buoyancy control and stagnation at depth	8	Internal pump component failure, excessive wear and tear	3	Commercially rated for pressures far beyond expected; can	8	192	Regularly test buoyancy engine after successful

						add a pressure sensor somewhere in the system for fault detection			recapture to ensure healthy operation
Solenoid	Loss of oil flow control	Potential loss of buoyancy control and stagnation at depth	8	Excessive wear and tear, water intrusion	2	Simplest possible control scheme implemented, can implement emergency bypass valve for resurfacing	8	128	Regularly test buoyancy engine after successful recapture to ensure healthy operation
Complete Assembly	Incorrect assembly	Incorrect fitting of parts, unreliable connections (mechanical, hydraulic, electrical), complete or intermittent loss of primary functions	9	Unclear assembly instructions, improperly mated connections	5	Thorough documentatio n has been compiled, all parts purchased or fabricated with tight tolerances	9	405	Review all documentati on before maintenance or disassembly, use care when making connections and ensure correct mating

Note: The Risk Priority Number (RPN) is the product of Severity, Occurrence, and Detection. For a more detailed breakdown of the severity, occurrence, and detection rankings, refer to Tables 11, 12, and 13 below.

Table 11. FMEA Severity Rankings [14]

Severity of Failure	Rank
Hazardous – No warning: Unsafe operation, without warning	10
Very high: Product inoperable; loss of primary function	8, 9
High: Product operable, but at a reduced level	6, 7
Low: Product operable; comfort or convenience items at reduced level	4, 5
Minor: Fit/finish, squeak/rattle don’t conform; average customer notices	2, 3
No effect	1

Table 12. FMEA Failure Occurrence Rankings [14]

Occurrence Criteria	Rank
Very High – almost certain failure, in a major way	10
High – similar designs have failed in the past	7, 8, 9
Moderate – similar designs have occasional moderate failure rates	4, 5, 6
Low – similar designs have low failure rates	2,3
Remote – unreasonable to expect failure	1

Table 13. FMEA Detection Rankings [14]

Detection	Criteria: Likelihood of Detection	Rank
Absolute Uncertainty	Design Control does not detect, or there is no Design Control	10
Very Remote	Very remote chance Control will detect	9
Remote	Remote chance Control will detect	8
Very Low	Very low chance Control will detect	7
Low	Low chance Control will detect	6
Moderate	Moderate chance Control will detect	5
Moderately High	Mod. High chance Control will detect	4
High	High chance Control will detect	3
Very High	Very high chance Control will detect	2
Almost Certain	Control almost certain to detect	1

Appendix D: Budget, Cost Breakdown, and Bill of Materials

The team was given a budget of $800, and this budget was spent judiciously to build the prototype. A breakdown of mechanical costs is given below in Table 14 and a breakdown of electrical costs is given below in Table 15. Together, these tables form the Bill of Materials for the prototype MicroFloat. The grand total is $783.45. Notably, the components reused from RUR (the micropump, solenoid, and related fittings), which could not be purchased due to supplier issues, are not included.

Table 14. Mechanical BOM and Cost Breakdown

Part Type	Part Name	Supplier	Quantity	Unit Price	Total Cost
Mechanical Components					
6061 Al Tube	OD 4.5", wall 0.125" * 36 in	Metal Supermarkets	1	$ 58.69	$ 58.69
Brass Hex Nipple	40142318	Grainger	1	$ 13.82	$ 13.82
Brass Threaded NPT Male with Zinc-Plated Steel Nut	51235K127	McMaster-Carr	1	$ 11.38	$ 11.38
0.125" thick Al Plate	10" x 10 in X 0.125"	Metal Supermarkets	1	$ 49.93	$ 49.93
6mm to 8mm Flexible Clamping Shaft Coupler	4002-0006-0008	servocity	1	$ 5.99	$ 5.99
6061 Al Bar	4.5" diameter, 6" length	Metal Supermarkets	1	$ 92.93	$ 92.93
Oil Reservoir	PVC	Lowe's	1	$ 5.00	$ 5.00
Switch	Switch	Blue Robotics	1	$ 15.00	$ 15.00
Air Vent	Air Vent	Blue Robotics	1	$ 9.00	$ 9.00
Bladder	TITLE Boxing Rubber Speed Bag Bladder	Title Boxing	1	$ 3.99	$ 11.97
1/2" to 1/8" Male to Female Adapter	50785K64	McMaster-Carr	1	$ 3.09	$ 3.09
O-ring	HNBR Parker KA157-70 O-Ring, Size 242,	Gallagher Fluid Seals	4	$ 1.96	$ 7.84
1/4" Through Wall Fitting	51055K525	McMaster-Carr	1	$ 4.19	$ 4.19
90 deg 1/4" to 1/8" Push to Connect Fitting	7397N48	McMaster-Carr	1	$ 12.43	$ 12.43
1/8" ID 1/4" OD Tube	55515K411	McMaster-Carr	2 Ft	$ 11.36	$ 11.36
1/8" ID 3/8" OD Tube with Male Fittings	5201K71	McMaster-Carr	1 Ft	$ 33.95	$ 33.95
O-ring	Nitrile 2-220	Parker	$4.00	$ 10.89	$ 10.89
2x3 Pin Shrouded Header 0.1"(pack of 10)	Generic 2x3 Pin Shrouded Header 0.1"(pack of 10) - - Amazon.com	Amazon	1	$ 5.77	$ 5.77
End Cap O-rings	342 Buna-N O-Ring, 70A Durometer, Square, Black, 3-5/8" ID, 4" OD, 3/16" Width	Amazon	1	$ 37.51	$ 37.51
				Subtotal:	$ 400.74

Table 15. Electrical BOM and Cost Breakdown

Part Type	Part Name	Supplier	Quantity	Unit Price	Total Cost
Electrical Components					
RF Transceiver Modules and Modems	Adafruit Industries LLC 3070	Digikey	1	$ 9.95	$ 9.95
Microcontroller	ESP32-DEVKITC-32D	snapeda	1	$ 15.00	$ 15.00
Motor	625857 Maxon	Maxongroup	1	$ 133.74	$ 133.74
Battery	Bioenno BLF-1206A 12V, 6Ah	powerwerx	1	$ 79.99	$ 79.99
Motor Controller	ICQUANZX DC 5V-36V 15A 3-Phase Brushless Motor Speed Controller Motor Control Board	Amazon	1	$ 22.99	$ 22.99
Diode (Battery to 5v)	BZX55C5V1-TAP	Mouser	2	$ 0.20	$ 0.40
connectors	PCB Terminal Blocks, Header, Wire-to-Board, 4 Position	TE	2	$ 1.81	$ 3.62
Battery Terminal Block Connectors	Phoenix Contact 1757019	alliedelec	1	$ 1.16	$ 1.16
Resistor (100 ohms)	R1	Mouser	2	$ 0.49	$ 0.98
GPS Module	NEO-6M GPS module	u-blox	1	$ 49.00	$ 49.00
protptype pressure sensor	Bar30 High-Resolution 300m Depth/Pressure Sensor	Blue Robotics	1	$ 36.00	$ 36.00
IR distance sensor	Sharp GP2Y0A21YK0F GP2Y0A21 10~80cm	Amazon	1	$ 9.88	$ 9.88
i2c chip	I2C Level Converter	Blue Robotics	1	$ 20.00	$ 20.00
				Subtotal:	$ 382.71