

# **MicroFloats: Swarmable, Autonomous Underwater Vehicles for Oceanic Studies**

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## 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 4 $\frac{7}{8}$  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.

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 density without changing its overall mass, allowing the MicroFloat to alter its buoyancy and therefore depth. 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, and sealing analyses to ensure it will meet all required specifications. The team will construct a functional, full-size prototype to validate the analyses in a real-world aquatic environment. Future work for this project will also include mechanical and electrical design iteration, development of a basic control system, and, further down the line, an implementation of true swarm behavior and communications.

## 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
- CWA: Clean Water Act
- EPA: United States Environmental Protection Agency
- GPS: Global Positioning System
- PCB: Printed Circuit Board
- PMEC: Pacific Marine Energy Center, the research institute that developed the “ $\mu$ Float”
- RUR: Rossum’s Undergraduate Robotics, the most recent capstone design team to work on the MicroFloat project
- pH/ORP: Sensor for measuring the pH and the oxidation reduction potential of a surrounding fluid
- CTD: Sensor for determining the conductivity, temperature, and depth in water, a primary tool for determining essential physical properties of sea water.
- NPT: National Pipe Taper, a US standard for tapered threads used on pipe and fitting.
- NPT Connection: A type of connection that rely on thread deformation to form leak free connection with the help of sealants.
- UAV: Underwater Autonomous Vehicle

## **1. Introduction and Background**

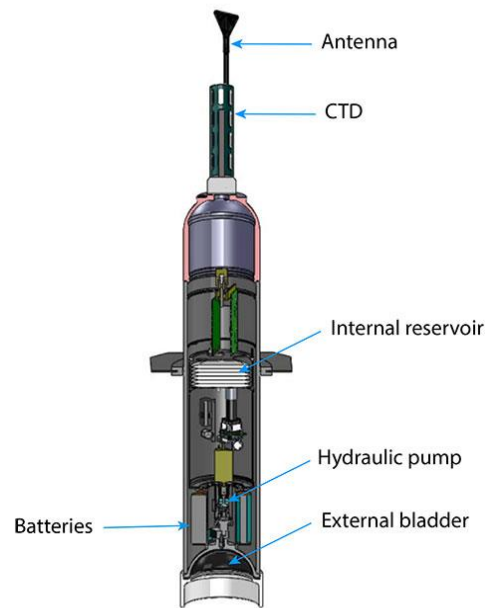
The deep ocean and hypersaline lakes present some of the most mysterious environments on the planet. These harsh, remote conditions support microbial life, as evidenced by methane cycling in the aquatic ecosystem, and a better understanding of this process can provide valuable insight into the relationship 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 4 $\frac{7}{8}$  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 stepping stone to potential solution concepts. A preliminary design is systematically selected and justified, and detailed mechanical analysis is presented to refine and validate the concept. Future work and project deliverables are described, illuminating 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].

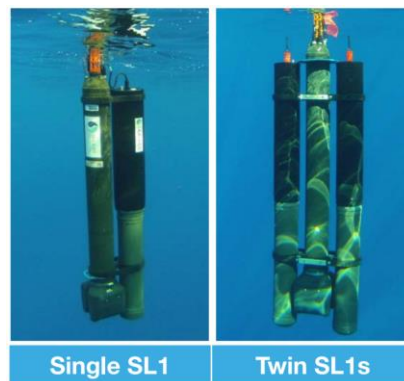
The Argo float, shown in Figure 1, was created by the Multi-National Argo Organization, which has worked with over 50 research agencies to make a float system for surveying the ocean. The Argo float can operate for years with little to no maintenance, diving to depths up to 2,000 m and rising to the 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.

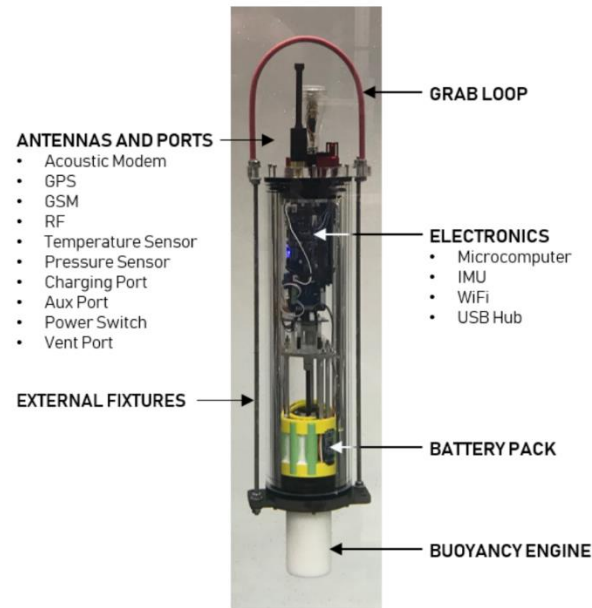
NKE Instrumentation offers a lineup of profiling floats with varying capabilities for a wide range of applications. One such float, the ARVOR I, is shown above in Figure 4. NKE is involved in the international Argo program and aims to offer a range of “standard” profiling floats that can collect CTD 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.



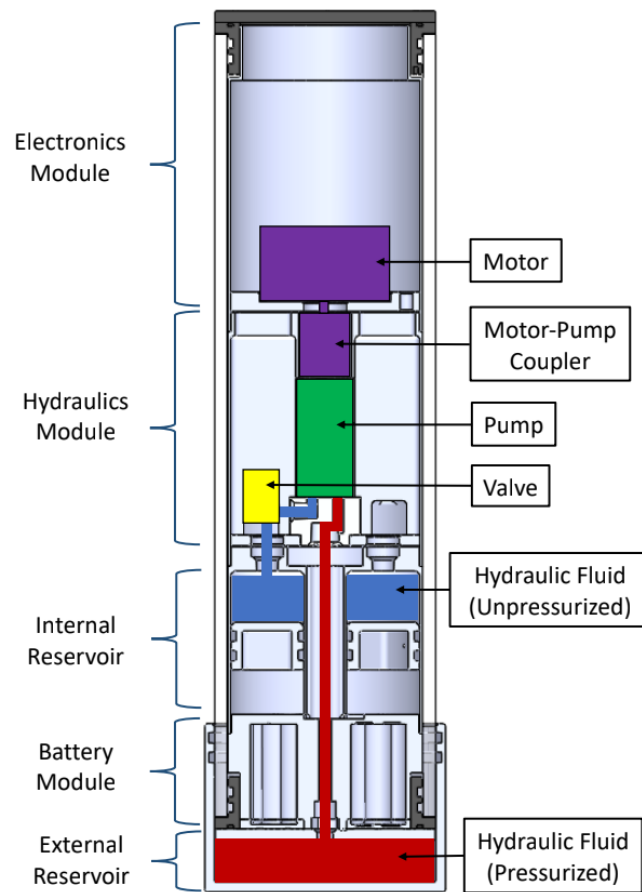
The Teledyne Marine APEX BioGeoChem float is another commercial float designed to support a wide variety of applications (Figure 5). It can accommodate CTD, dissolved oxygen, and pH sensors as well as a fluorometer. It is a large vehicle, measuring 6.5 inches in diameter and 55 inches in length. This 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  $\mu$ Float unit detailing its primary subsystems and components [2].

Another design, dubbed “ $\mu$ Float”, is shown above in Figure 6. The  $\mu$ Float 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  $\mu$ Float 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  $\mu$ Float 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.

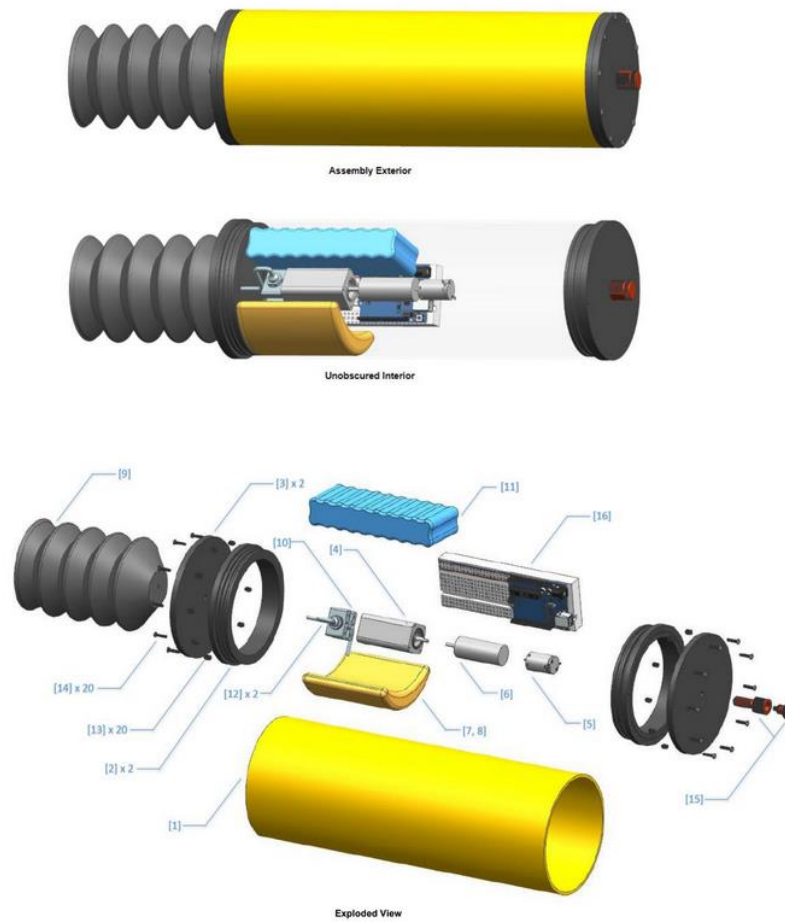


Figure 8. Assembly model of buoyancy engine developed by “Together We Swim” [4].

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.

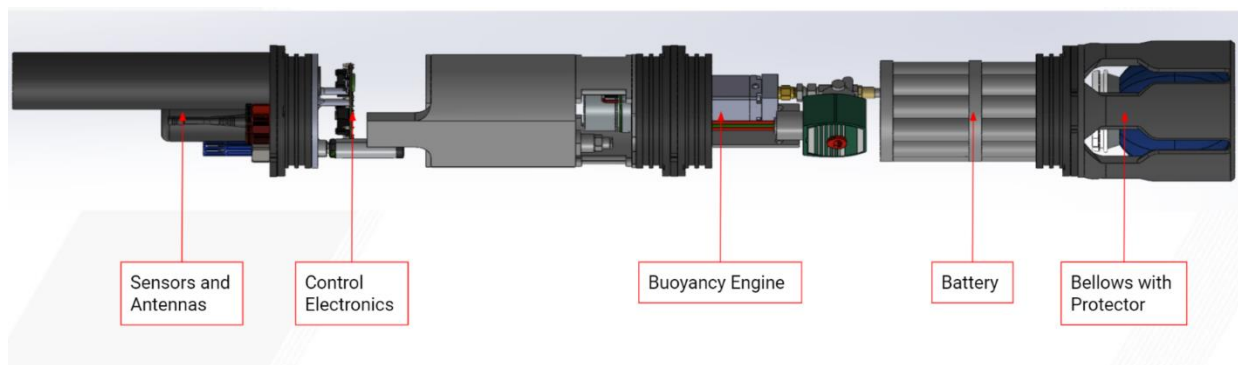


Figure 9. Rossum’s Undergraduate Robotics MicroFloat prototype design [5].

### 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  $\mu\text{g/L}$  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  $\mu\text{g/L}$ . 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 Rhode 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.

		Column #	1	2	3	4	5	6	7	8
		Direction of Improvement	▲	▲	▲	▲	▼	▼	▲	◇
Category	Weight	<div>Engineering Requirements</div> <div>Customer Requirements (Explicit and Implicit)</div>	Tensile Strength (Mpa)	Compressive Strength (Mpa)	Sensing Range (m)	Motion Range (# cycles)	Mass (kg)	Cost (\$)	Battery Life (weeks)	Resolution
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.

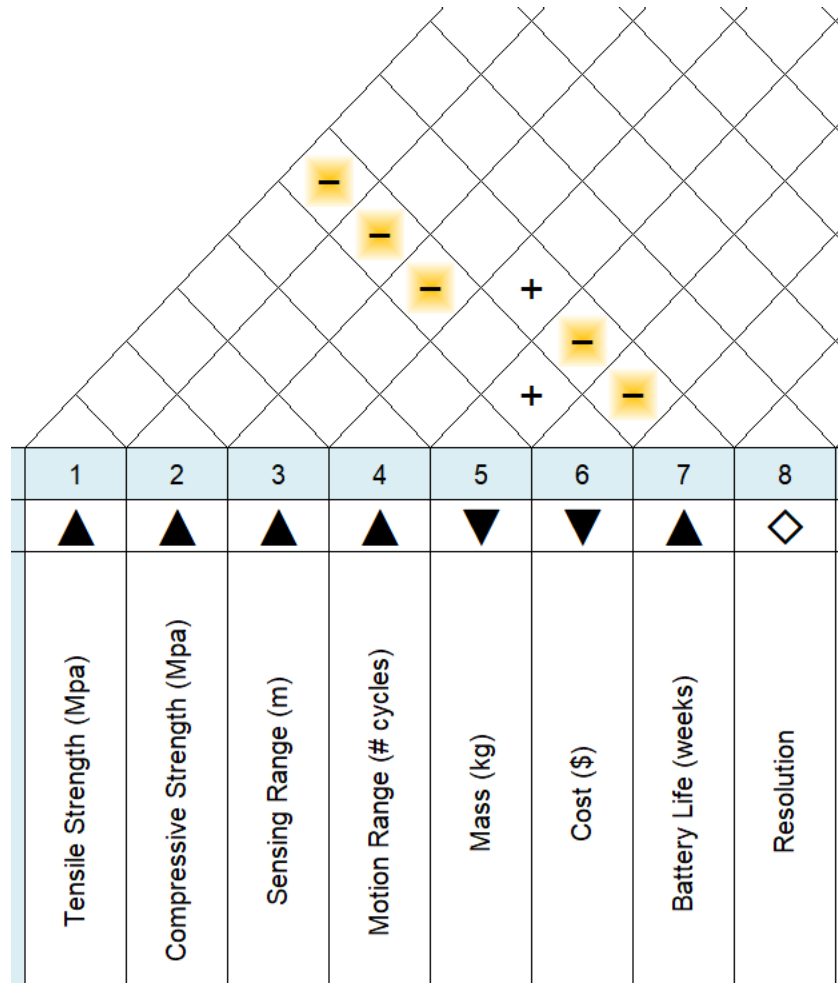


Figure 11. Synergy and interference evaluation in the roof of the House of Quality.

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
	<i>Operation</i>	
D	Withstand hydrostatic pressure at depths up to 750 m	Research Project Pls 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 Pls 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
	<i>Geometry</i>	
D	Cylindrical form factor (A-size sonobuoy); 4.875" diameter, 36" length	Research Project Pls and Dr. West
	<i>Material</i>	
D	Resist corrosion; maintain surface quality and no loss of mechanical strength	Project Scope
	<i>Cost</i>	
W	Inexpensive unit price relative to commercial UAVs; \$800	Research Project Pls 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.



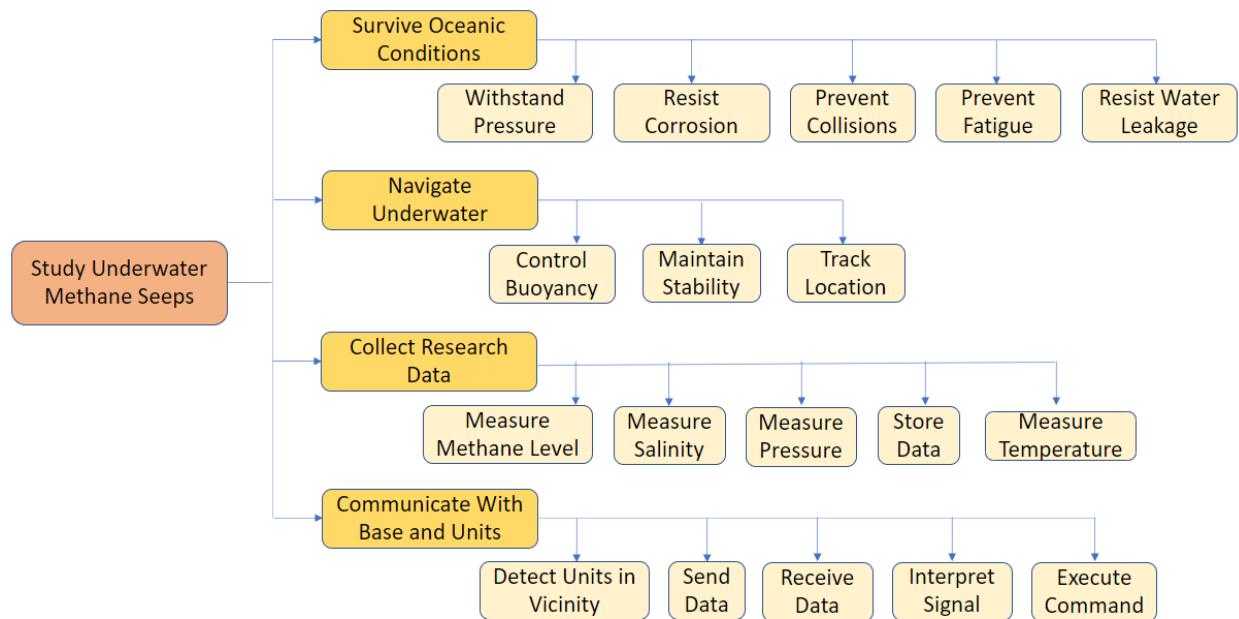


Figure 12. MicroFloat function tree delineating the major sub-functions necessary to complete ocean research missions.

## 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.












































Functions	Concept 1	Concept 2	Concept 3	Concept 4	Functions	Concept 1	Concept 2	Concept 3	Concept 4
Maintain Stability/Orientation	Fins 	Hang Mass from Float 	High Internal COM 	Low Internal COM 	Resist Corrosion	Corrosion Resistant Material 	Barrier Coating 	Anodized surface 	Hot-Dip Galvanization 
Control Buoyancy	Ballast System 	Screw Driven 	Pressurized Piston 	Bellows 	Withstand Pressure at 750m	Properly Sized Body 	Pressurized Cylinder 	Flexible frame 	Spherical vessel 
Track Location	Use GPS 	Use Sonar for Depth Sensing 	Communicate with other units 	9-axis imu (gyroscope, accelerometer, compass) 	Resist Water Leakage	Capped Cylinder 	O-Ring/Gasket 	Use Sealant 	Weld the seam 

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	Interchangeable 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 bellows. 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.

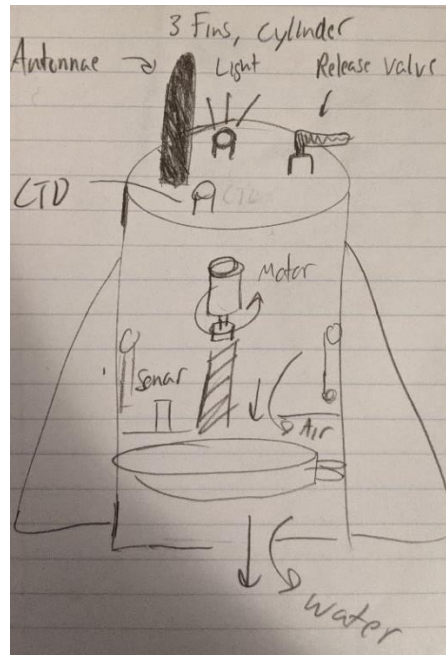


Figure 14. Concept sketch of a cylindrical and finned design using an electric motor to mechanically drive a piston, drawing in or expelling seawater to alter the device's mass and therefore buoyancy.

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.

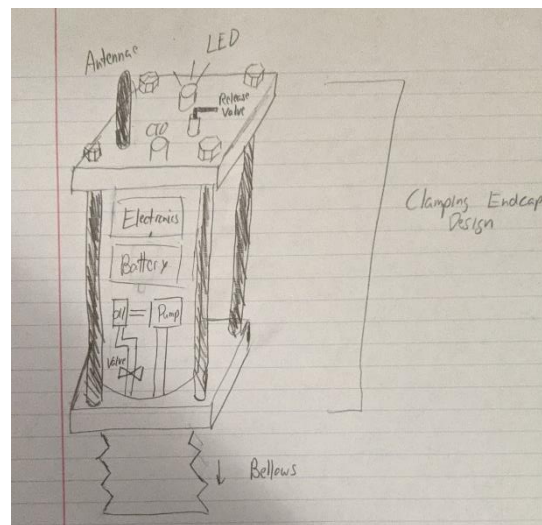
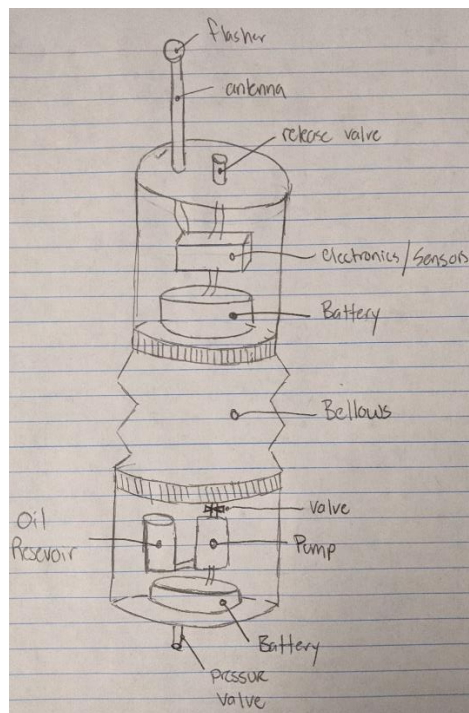


Figure 15. Concept sketch of a cylindrical design with an oil-driven hydraulic bellows and clamped plate endcaps.

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.



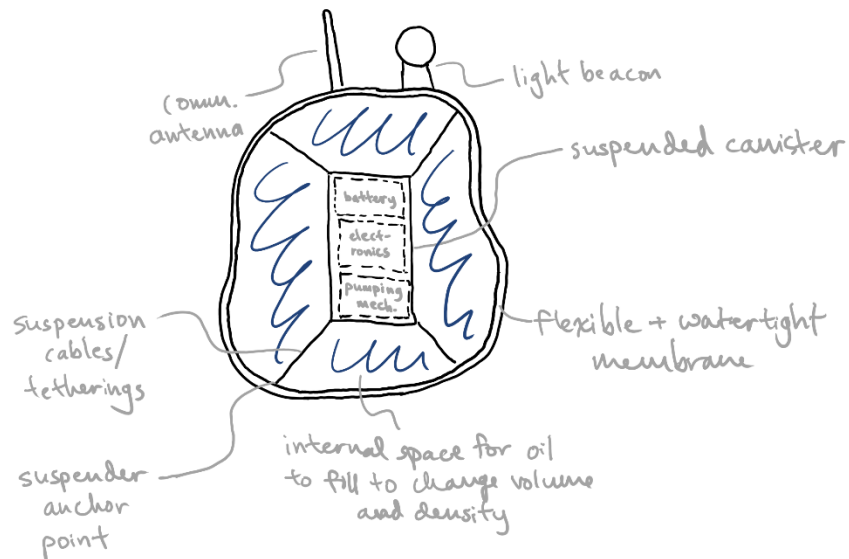
*Figure 16.* Concept sketch of a cylindrical design with a centrally located hydraulic bellows. The design incorporates a degree of modularity by separating the control and sensing electronics from the hydraulic and actuation hardware.

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.

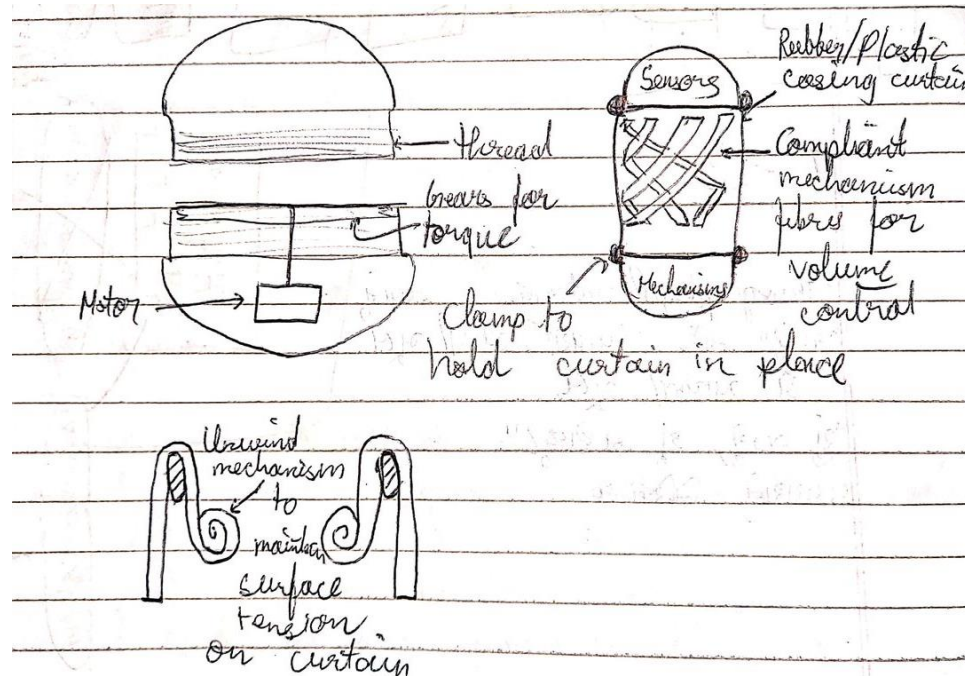


Figure 19. Concept sketch of a spherical design utilizing a centrally located hydraulic bellows. The design includes a novel compliant mechanism to actuate the bellows.

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	

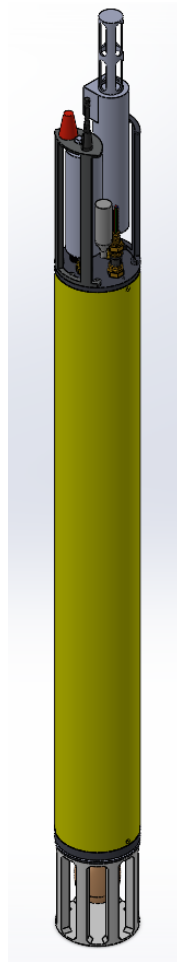
The most crucial criteria are assigned a relative importance value of 10, including the ability to measure methane seeps, alter buoyancy, and withstand ocean conditions for an extended time at 750 m below the surface. These criteria are most important because they are essential to the vehicle's successful 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).

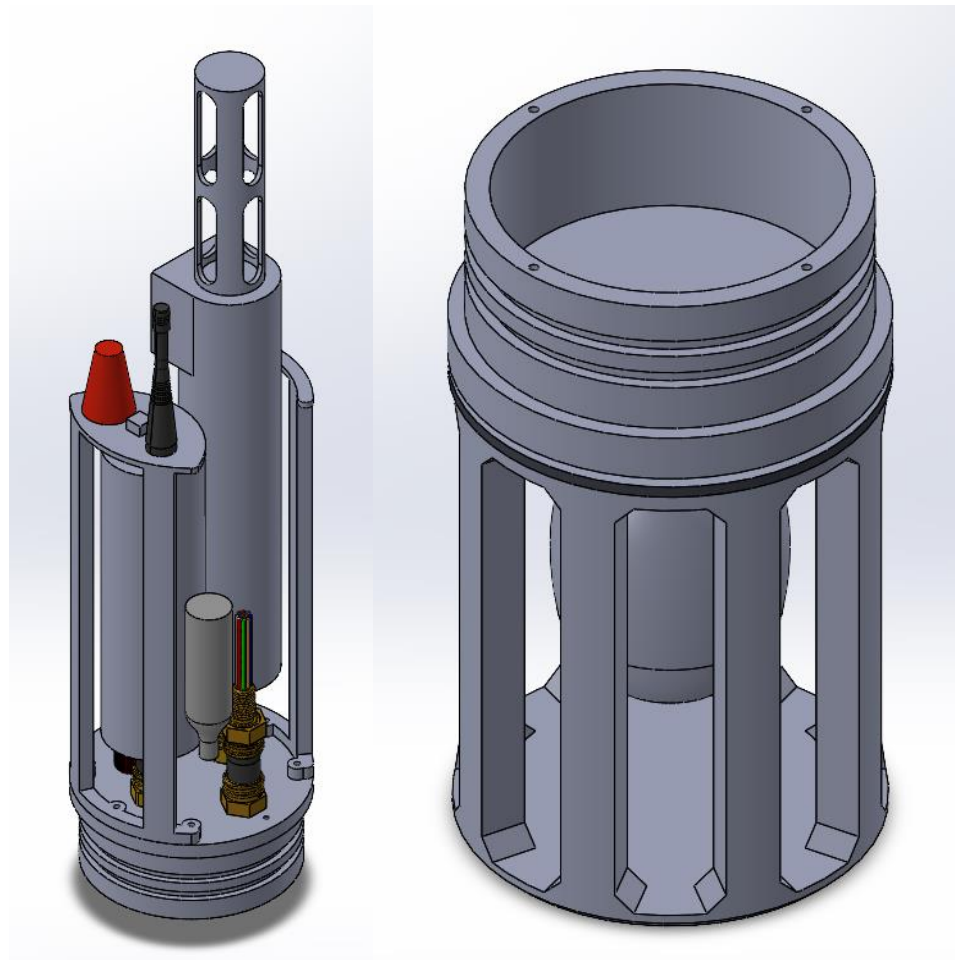


*Figure 20. MicroFloat CAD assembly model.*

The detailed design for the MicroFloat is divided into two sections: the external design of the vessel, and the internal design layout for the electronics and hardware. 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 needed to be maximized within the overall size constraints of the MicroFloat, while weight needed to be minimized. The in-depth 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.

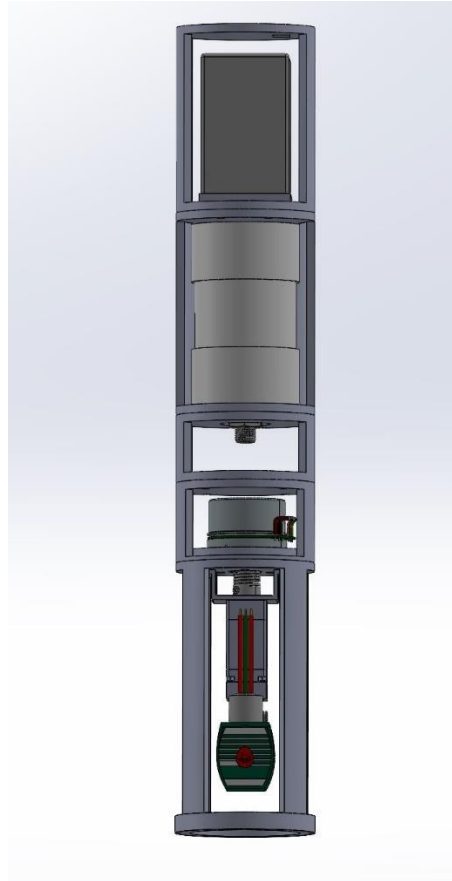
For the body of the MicroFloat, the team identified a suitable Al 6061 pipe that satisfies the strength and geometry requirements from the pressure calculations. The pipe is sealed at both ends by a set of machined caps that employ a double O-ring seal that will provide adequate and redundant sealing 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 includes inward facing tapped holes for mounting the internal hardware. The top and bottom Cap Assemblies can be viewed below in Figure 21.

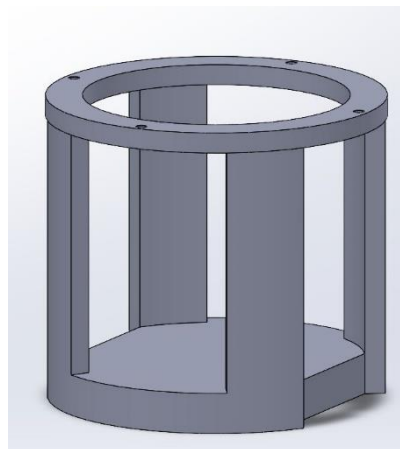


*Figure 21a/b. Top cap assembly / Bottom cap assembly.*

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 flow 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 (Figure 22).



*Figure 22a.* Bottom internal frame assembly, showing from top to bottom the battery, oil reservoir, oil pump motor, oil pump, and solenoid. Hydraulic lines are not shown.



*Figure 22b.* Top internal frame without PCBs, designed to be modular and easily removable.

## 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 inherent 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 an ocean of 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)
<b>Electrical Componenets</b>			
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
<b>Mechanical Components</b>			
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 Resevoir		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:

$$\text{mass of water displaced} = \text{total weight of microfloat}$$

$$\text{mass of water displaced} = \text{total outer volume of microfloat} * \text{density of sea water}$$

$$\text{total weight of microfloat} = \text{Aluminum shell weight} + \text{total weight of electrical and mechanical components}$$

The results of the calculations performed are tabulated in figure 20 and it shows that in order to achieve neutral buoyancy, the design is required to 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 definitely 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 <sup>3</sup> )	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 <sup>3</sup> )	1.02813
Length Required for Neutral Buoyancy (m)	0.85
Methane Sensor Exposed Volume (in <sup>3</sup> )	18.2
pH/O.R.P. Sensor Exposed Volume (in <sup>3</sup> )	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 signify that the MicroFloat design would be withstand load due to water pressure at 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 <sup>4</sup> )	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  $\rho_{w1000} = 1032.85 \text{ kg} \cdot \text{m}^{-3}$  [10]. The density of seawater at surface is  $\rho_{w0} = 1024.5 \pm 4.5 \text{ kg} \cdot \text{m}^{-3}$ . Assuming that the uncertainty carries by depth, the density of the seawater at the depth of 1000m is  $\rho_w = 1032.85 \pm 4.5 \text{ kg} \cdot \text{m}^{-3}$ . Approximating a linear density profile provides an estimated density at the depth of 750m as  $\rho_{w750} = 1030.76 \pm 4.5 \text{ kg} \cdot \text{m}^{-3}$ . The maximum pressure at 1000 m is

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

The maximum pressure at 750 m is

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

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  $D = 4.5 \pm 0.035 \text{ in}$ . The uncertainty is standard manufacturing error for dimensions that size platforms such as McMaster-Carr. The rough length is  $L = 36 \text{ in}$ . The dimensions provide volume as follows:

$$V = 572.56 \pm 4.45 \text{ in}^3$$

The average density of seawater across the first 1000m is

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

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

$$m = 9651.7 \pm 75.1 \text{ g}$$

Based on the design constrains, outer diameter of the cap is  $D = 4.5 \pm 0.035 \text{ in}$ . 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 disc 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:

$$\sigma_{\infty} = p = 1467.91 \pm 8.27 \text{ psi}$$

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

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

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

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

$$\sigma_z = p = 1467.91 \pm 8.27 \text{ psi}$$

$$\sigma_{\theta} = 0$$

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

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

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

$$F_r = p A_i = 20824 \pm 375.25 \text{ lb}$$

$$A_r = \pi D_i t = 1.66897 \pm 0.09455 \text{ in}^2$$

$$\tau = \frac{F_r}{A_r} = 12477 \pm 741.74 \text{ psi}$$

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.

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

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:

$$D = 4.5 \pm 0.035 \text{ in}$$

$$t = 0.125 \pm 0.007 \text{ in}$$

$$D_i = 4.25 \pm 0.0364 \text{ in}$$

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

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

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:

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

$$\sigma_r = \frac{D_i^2 p}{D^2 - D_i^2} \left( 1 - \frac{D^2}{D_i^2} \right) = p = 1467.91 \pm 8.27 \text{ psi}$$

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.

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

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  $3 \times 10^4$  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 the appendix.

*Table 7. Marin Factors to Correct Fatigue Strength*

<b>Factor</b>	<b>Correction Significance</b>	<b>Value</b>
$k_a$	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  $S_f = k_a k_b k_c k_d k_e k_f \cdot S'_f = 93.98 \text{ MPa}$  at  $10^5$  cycles and  $108.70 \text{ MPa}$  at  $3 \times 10^4$  cycles. The minimum pressure applied to the MicroFloat is atmospheric,  $p_{atm} = 0.1013 \text{ MPa}$ , while the maximum pressure is  $p_{max} = 1098.7 \text{ psi} = 7.58 \text{ MPa}$ . This maximum corresponds to the hydrostatic water pressure at a depth of 750 meters. To ensure adequate overhead in the strength of the design, the analysis will instead use the hydrostatic water pressure at a depth of 1000 meters,  $p_{max} = 1467.9 \text{ psi} = 10.1 \text{ MPa}$ . 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  $\sigma'_0 = 1.45 \text{ MPa}$  and  $\sigma'_{1000} = 144.7 \text{ MPa}$ , respectively. These minimum and maximum values lead to a midrange stress of  $\sigma'_m = 73.08 \text{ MPa}$  and a stress amplitude of  $\sigma'_a = 71.63 \text{ MPa}$ . 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  $3 \times 10^4$  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  $3 \times 10^4$  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.

## 10. 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.

## 11. 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)	Ensures 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. Dahrius Abdelnur modelled the outer shell of the MicroFloat design, sourced the required materials and components, and prepared the fabrication package. Joseph Jarman modelled the internal components and assembly of the MicroFloat, understood how to achieve water tightness at high pressure, finished the fabrication package, and helped write the weekly emails. 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. Terence Lui performed engineering analysis on the mechanical design, worked on environmental consideration, handled the BOM for budget and weight calculations, and helped with sourcing the required materials and components. Vatsal Trivedi conducted engineering analysis on mechanical design, he identified possible stress concentration on the whole assembly and analyzed the possible modes of failure. He also purchased the mechanical components.



## 12. Conclusions, Future Work, and Project Deliverables

The team has followed the schedule shown below in the Gantt chart in Figure 23. It is important to note that this Gantt chart serves only as a guide for the team's progress, and deliverables and sub-tasks will emerge and get assigned and completed more organically than can be shown on the chart. Future milestone tasks will also get updated as the team gains a clearer picture of what must be done during the prototyping, testing, and verification stages of the project.

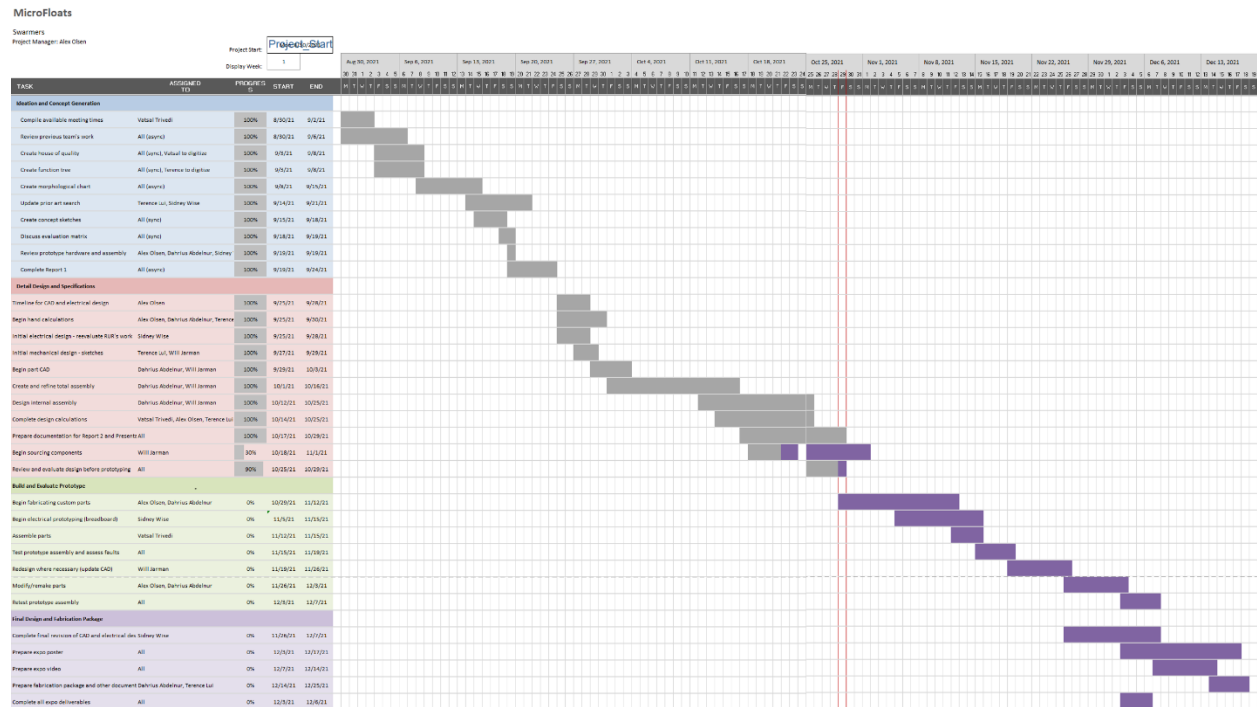


Figure 23. Gantt chart showing the team's current progress in the project so far and an outline for general, larger upcoming tasks.

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 main design challenges that are faced by the team include buoyancy control, waterproofing at depth, and withstanding the pressure at depth while keeping the overall weight low. In response to these challenges, the team is currently polishing the detailed design presented in this document. The next phase of the project is design validation, in which a functional prototype will be manufactured and tested under

representative conditions to ensure that the design calculations are accurate. Electronics parts are ordered and metal stock to build the cylinder and endcaps is on the way. The team has consulted with a machinist to discuss the manufacturing of the top and bottom endcaps from a single piece of round bar aluminum billet. O-rings and appropriate fasteners will also be sourced so true watertightness may be tested and verified. The team also intends to develop a basic control algorithm to assess how well the design can reliably and accurately change its depth in water given a set of instructions. Components that are impractical to source or manufacture, such as the methane and pH sensors as well as the top grab handle and sensor cage, will be replaced with 3D-printed analogs that can validate the geometry and mechanical function. This prototype will be put to the test in a diving pool as well as an acoustic chamber, and from there the team will implement iterative improvements as necessary to take another step closer to the finalized design.

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## Appendix

### *Marin Factor Calculations:*

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

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

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

$$k_c = 0.85 \text{ for pure bending loads [13]}$$

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

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

$k_f = 0.75$  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 will 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:*

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

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]

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

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]

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

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]