MicroFloats: Swarmable, Autonomous Underwater Vehicles for Oceanic Studies

Team: *Swarmers*

ME/ECE 4723 A – Capstone Design

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Executive Summary

Till date, the oceans remain one of the most under-sampled and unquantified environments on the planet. This is due to its vast size and inherent complexity. Ocean scientists need small aquatic robots that can be deployed in swarms to measure and store data regarding methane seeps over a large area of the ocean; this is the main function of the MicroFloat. The MicroFloat will need to be a small device under 4.875 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 and it must be able to survive depths of up to 750 meters. The float will also need to be able to collect methane data using sensors and store that data over the course of its two-week mission, after which the float must transmit its data and communicate with its operators from the surface. The primary design goal is to create an autonomous robot that is robust, power efficient, and easily serviceable. Ultimately, the vehicle should be able to be deployed in a swarm to survey a vast area of ocean water.

To begin the ideation process, the team used both a function tree and a house of quality to determine the overarching customer requirements and engineering design specifications. The team then used an evaluation matrix to determine the importance of key requirements such as measuring pressure, maintaining strong battery life, withstanding pressure, and remaining easy to fabricate, operate, and maintain. After exploring multiple designs, the team ultimately decided on using a cylindrical aluminum shell that uses an oil driven bellows system for locomotion. The oil is pumped into the bellows and induces a change in the overall system displacement which allows the MicroFloat to alter its buoyancy and therefore depth. The team converged to the design due to its survivability, low weight, power efficiency, and ease of deployment. Prototype testing for the bellows system will be conducted in a pool, and if an appropriate hydrostatic pressure testing vessel can be located, the MicroFloat’s ability to operate at maximum depth will be tested as well. If a pressure testing vessel cannot be found, the design will be simulated using FEA. These tests will serve as proof of concept that the MicroFloat will be able to change its depth in water and withstand the pressure located at its maximum depth rating. Future work for this project will include mechanical and electrical system improvement, as well as implementing a modular system for sensors other than methane to be placed in the MicroFloat. Further work will also be needed to implement true Lagrangian swarm behavior for the MicroFloat.

Glossary

- 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 “µFloat”
- RUR: Rossum’s Undergraduate Robotics, the most recent capstone design team to work on the MicroFloat project

1. Introduction and Background

The ocean, due to its vast size, is the most unexplored and under sampled ecology on our planet. The Swarmers' task is to create a small aquatic robot that can be deployed in swarms to sample and record data regarding methane seeps over large swaths of the ocean. This device will use a quasi-Lagrangian system to move laterally, passively riding underwater currents. The mission of the robot is to explore methane seeps in the Gulf of Mexico. This project aims to design the electrical and mechanical systems for a single unit. The main challenges faced in this design process include waterproofing, withstanding high pressure, creating a buoyancy engine, developing communication, and enduring long missions. The desired solution is a robot that is 4.875 inches in diameter and at most 36 inches long. The robot must be able to change its elevation by altering its buoyancy and this will be achieved by changing the robot's volume. 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 m/s. Watertightness of the design and its ability to change its buoyancy are critical and will be tested in a pool. The battery life of the device will be simulated based on expected operating conditions. In the case that an appropriate hydrostatic pressure testing vessel can be located, the prototype's ability to withstand pressure will be tested. In the remainder of this document, prior art and applicable patents are listed and discussed. The codes, standards, customer requirements, and engineering considerations are detailed. These are used to generate potential solution concepts that are then explored in the ideation process. A preliminary design is systematically selected and justified. The future schedule of the group and team member contributions are also specified.

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.

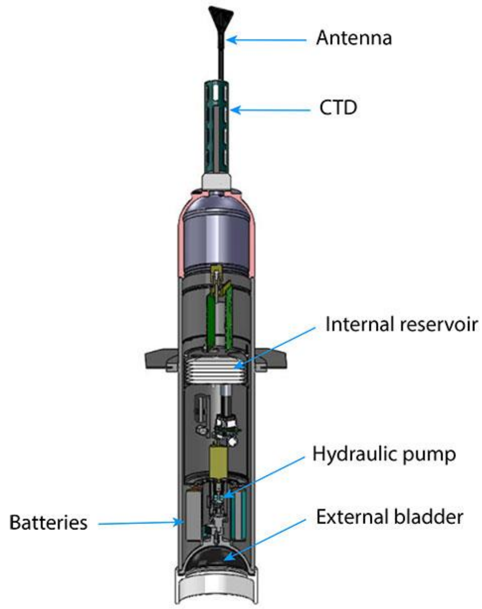

Figure 1. Section view of the Argo float system displaying primary internal components. [1]

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 has been operating 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.

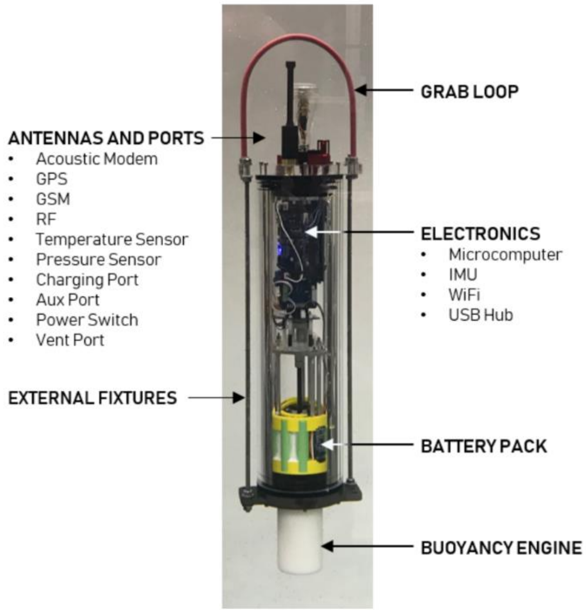

Figure 2. Image of a prototype µFloat unit detailing its primary subsystems and components. [2]

Another design, dubbed “µFloat”, is shown above in Figure 2. 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 3. 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.

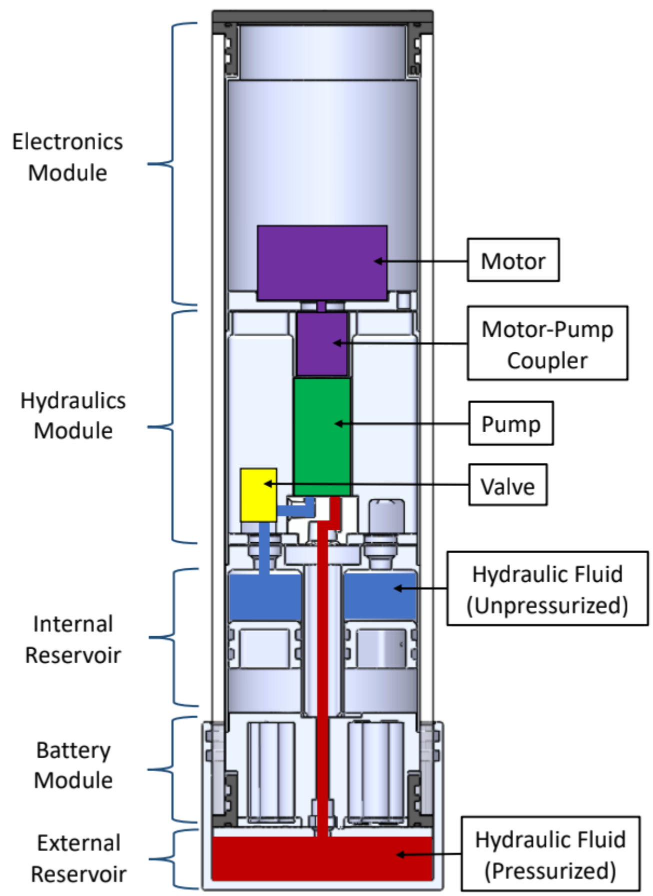

Figure 3. Cutaway view of the Lagrangian profiler developed by a Georgia Tech VIP team. [3]

"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 4.

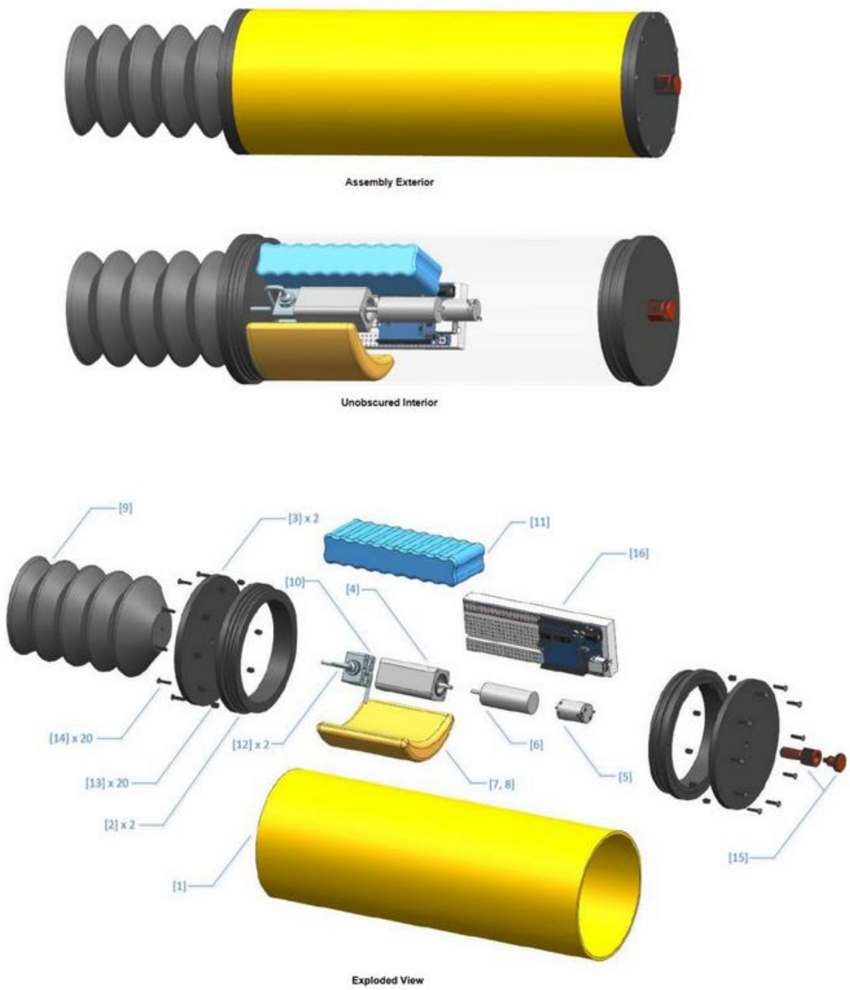

Figure 4. Assembly model of buoyancy engine developed by "Together We Swim". [4]

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 5 depicts a model of RUR's final design with the cylindrical casings removed.

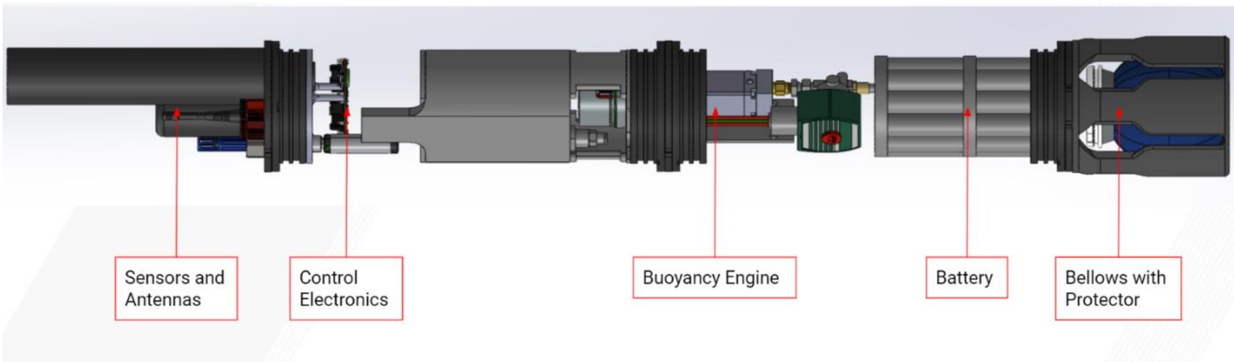

Figure 5. Rossum's Undergraduate Robotics MicroFloat prototype design. [5]

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 sealless 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 sealless, 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 6 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 6. 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 7, cost and battery life interfere with several other requirements but take a higher priority in the decision-making process.

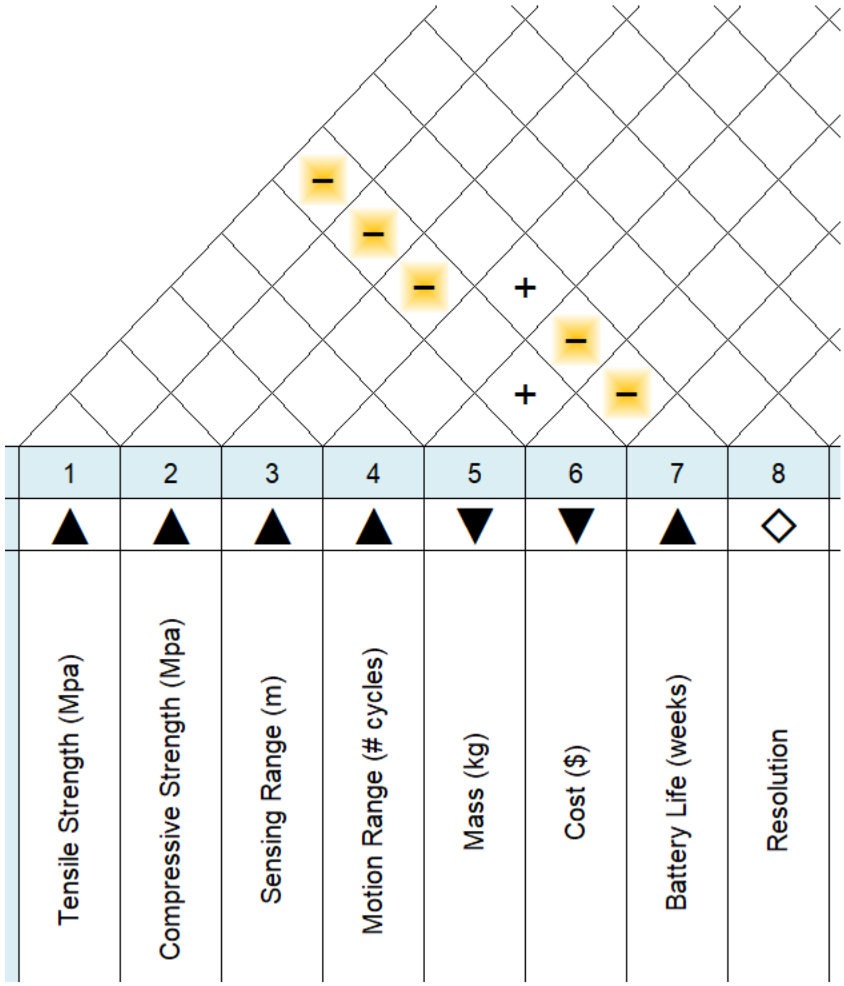

Figure 7. Synergy and interference evaluation in the roof of the House of Quality.

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. The responsibilities are currently assigned based on expertise and are subject to change as dictated by the project timeline and interdependence discovered as progress is made through the project.

Table 1. Specification Sheet

		Issued:	
	Specification		
	For: MicroFloat		Page 1
D/W	**Requirements**	**Resp**	**Source**
	Geometry		
W	4.875" OD 36" Length	Will	Project Goal
	Kinematics and Forces		
D	Move Vertically	Terence	Project Goal
D	Resist Rotation	Vatsal	Instability Analysis
D	Alter Buoyancy	Alex	Project Goal
	Material		
D	Corrosion Resistance	Alex	Environment Aanlysis
D	Pressure Tolerance	Dahrius	Project Goal
	Safety		
W	Collision Prevention	Vatsal	Sustainability Consideration
	Production		
W	Conventional Methods	Will	Timeline Constraints
	Assembly		
D	Watertight Shell	Terence	Project Goal
	Costs		
W	<$800	Sidney	Project Goal

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 8. 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.

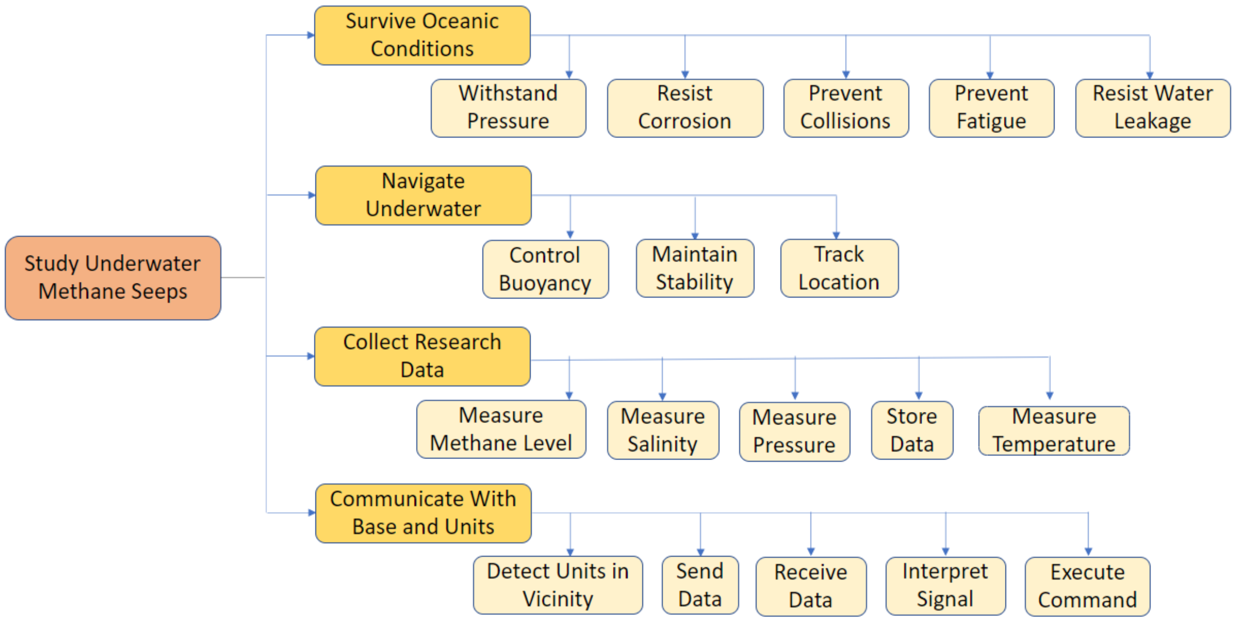

Figure 8. MicroFloat function tree delineating the major sub-functions necessary to complete ocean research missions.

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 9a and 9b, 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.

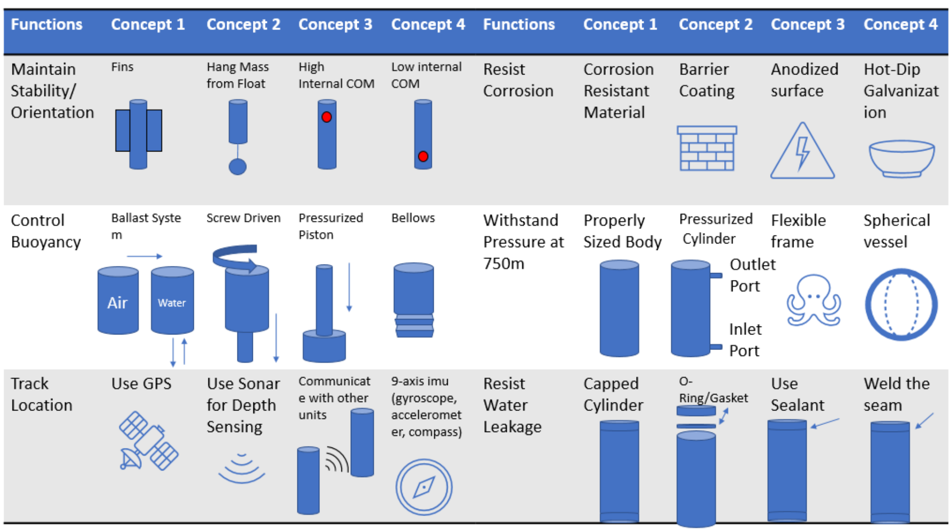

Figure 9a. First half of morphological chart used in ideation process, capturing design ideas for the specified functions.

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 9b. 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 thought 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 solution-rom 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 10 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.

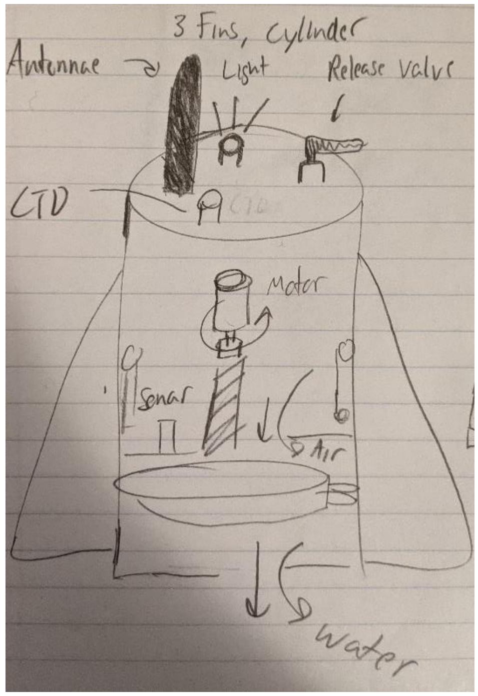

Figure 10. Concept sketch of a cylindrical and finned design using an electric motor to mechanically drive a piston, drawing in or expelling seawater to alter the device's mass and therefore buoyancy.

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 11, also utilizes a cylindrical base but includes additional components to add to the structural rigidity and watertightness of the design.

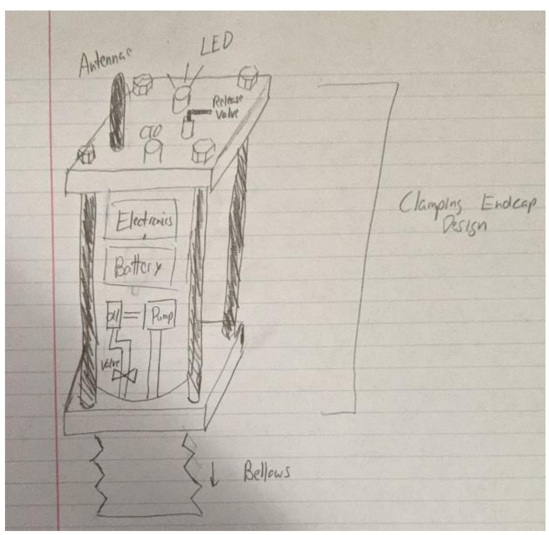

Figure 11. Concept sketch of a cylindrical design with an oil-driven hydraulic bellows and clamped plate endcaps.

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 12, changes the location of the bellows to being in the center and separates the unit into two halves. One half of the sphere is dedicated to 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.

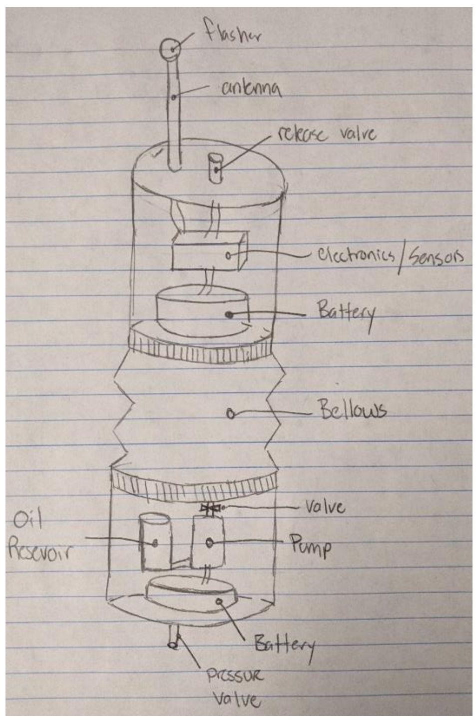

Figure 12. Concept sketch of a cylindrical design with a centrally located hydraulic bellows. The design incorporates a degree of modularity by separating the control and sensing electronics from the hydraulic and actuation hardware.

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 13.

Figure 13. 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 14.

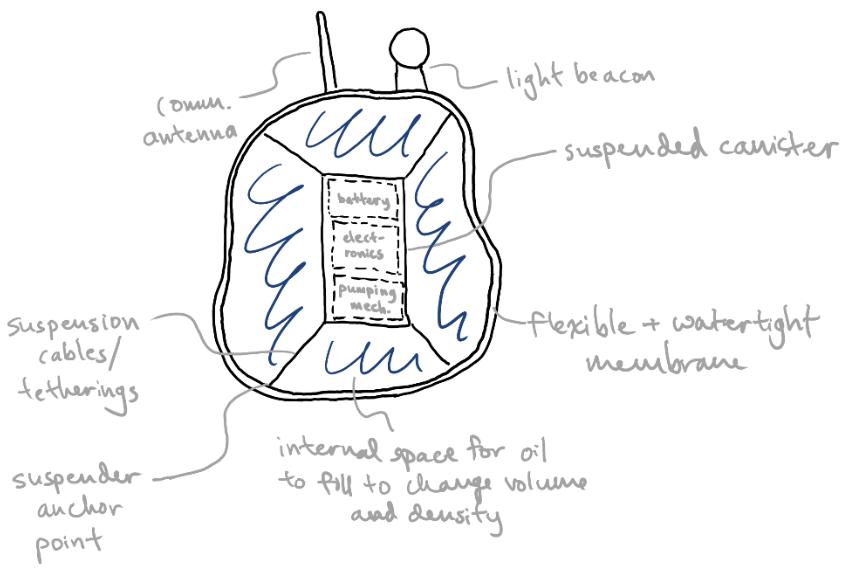

Figure 14. Concept sketch of a nonrigid balloon design that can deform with external forces. Control electronics and hardware are suspended inside an internal canister, and hydraulic oil fills the cavity between the canister and the surrounding membrane.

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 15 below.

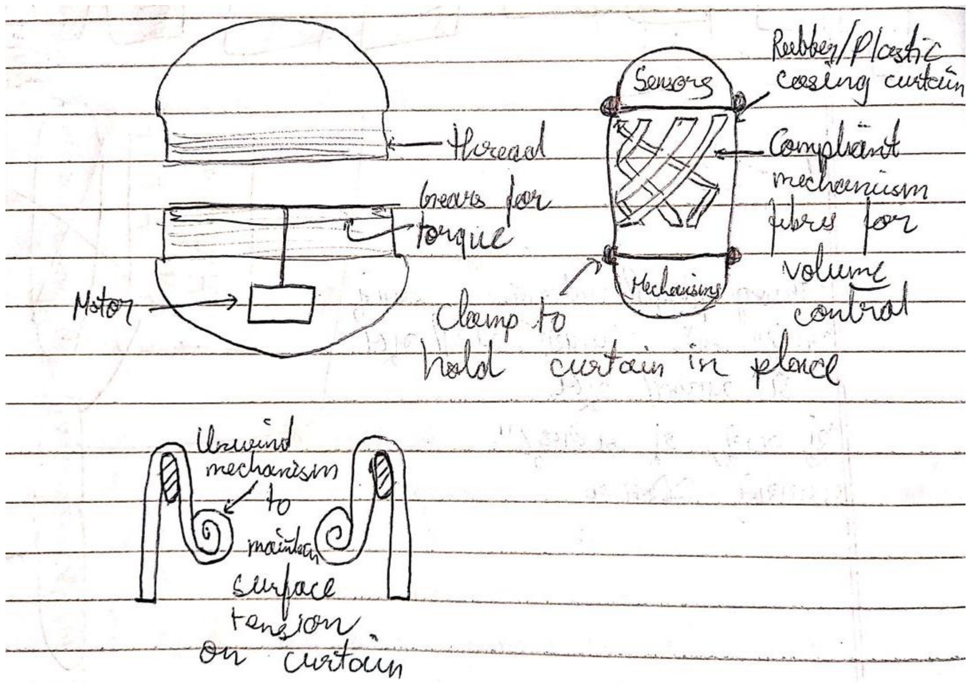

Figure 15. Concept sketch of a spherical design utilizing a centrally located hydraulic bellows. The design includes a novel compliant mechanism to actuate the bellows.

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 function; 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 depicted in Figure 12. 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 13) and the spherical design with an external oil sack (shown in Figure 14) 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. Therefore, the team will move forward with a cylindrical design, which offers the best compromise between performance and practicality, and will experiment with bottom and central bellows placement as well as new assembly design.

8. Team Member Contributions

Each team member agreed to take on a specific group role, and assignments are outlined in Table 3 below. As the project manager, Alexander Olsen arranged group meetings and outlined weekly tasks, organized the project Gantt chart (shown below in Figure 16), and sent the weekly status emails. He also wrote the concept selection and justification section of this document and acted as a primary editor. As the controls and fabrication lead, Dahrius Abdelnur helped assess the parts and inventory available in the lab, helped in considerations regarding manufacturability of different designs, and focused on the idea generation portions of the report and presentation. Joseph Jarman has presented the weekly presentations in lab. He also wrote the executive summary, introduction, and conclusion portion of this essay. As a software lead, Vatsal Trivedi has started making the Capstone Website. He also took charge of understanding customer requirements and translating them to engineering requirements to develop product specifications. Terence Lui worked on identifying the codes and standards that this project would reference throughout its development and helped identify components in the lab. Sidney Wise identified the prior art and wrote the section covering those findings, and she has also begun identifying electronics components that will be useful for fulfilling the electrical requirements for the design.

Table 3. 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	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 on any custom software

9. Conclusions, Future Work, and Project Deliverables

The team has followed the schedule shown below in the Gantt chart in Figure 16. A complete Gantt chart laying out the entire project timeline is presented in the appendix.

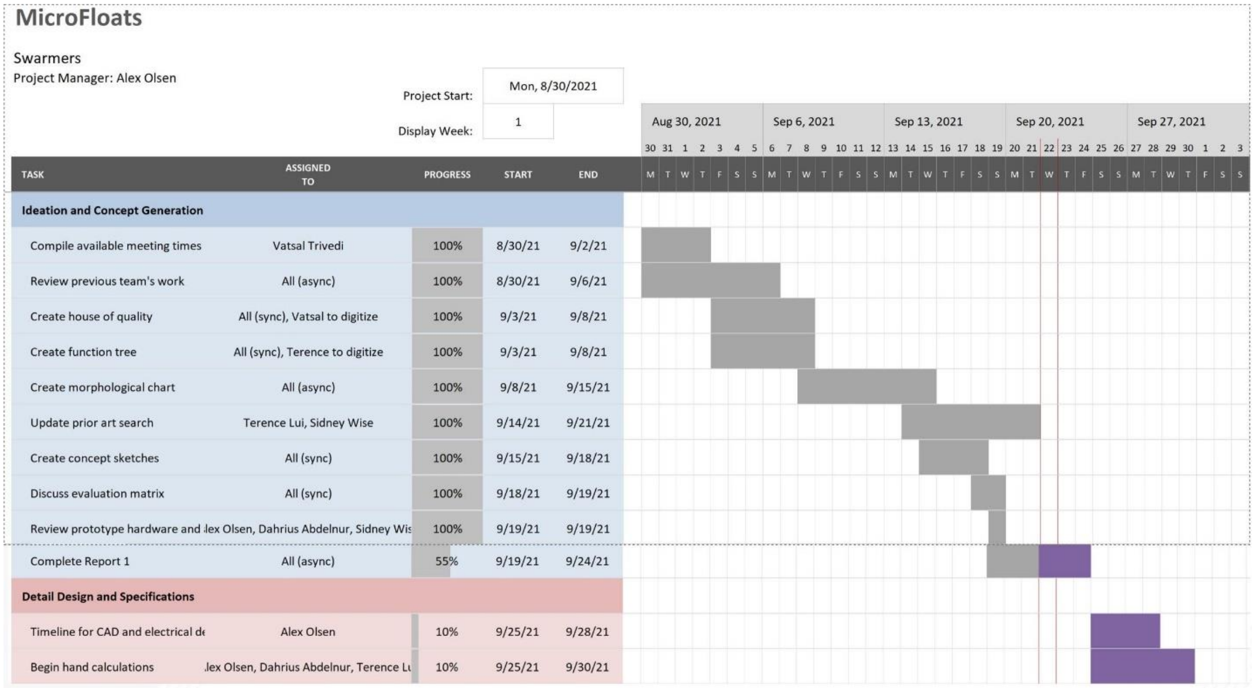

Figure 16. Gantt chart showing teams initial schedule and progress towards current deliverables.

Each task is a main function that is further divided into sub-functions that are split among the team members. This schedule is in place to make sure the team stays on track and completes all the necessary tasks before the expo deadline.

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 working on a solution of an aluminum cylinder that uses an oil driven bellows system to change elevation. The aluminum cylinder bellows design was considered the best option due to its relatively low weight, power efficiency, and its numerous ways to be deployed.

The team is currently working on the electrical and mechanical design and CAD simulations of these devices. The initial ideation and evaluation stage was successful, and these stages allowed the team to raise and explore overarching questions that were had about each design. The design phase focuses on component selection and initial simulations that will be used as a proof of concept.

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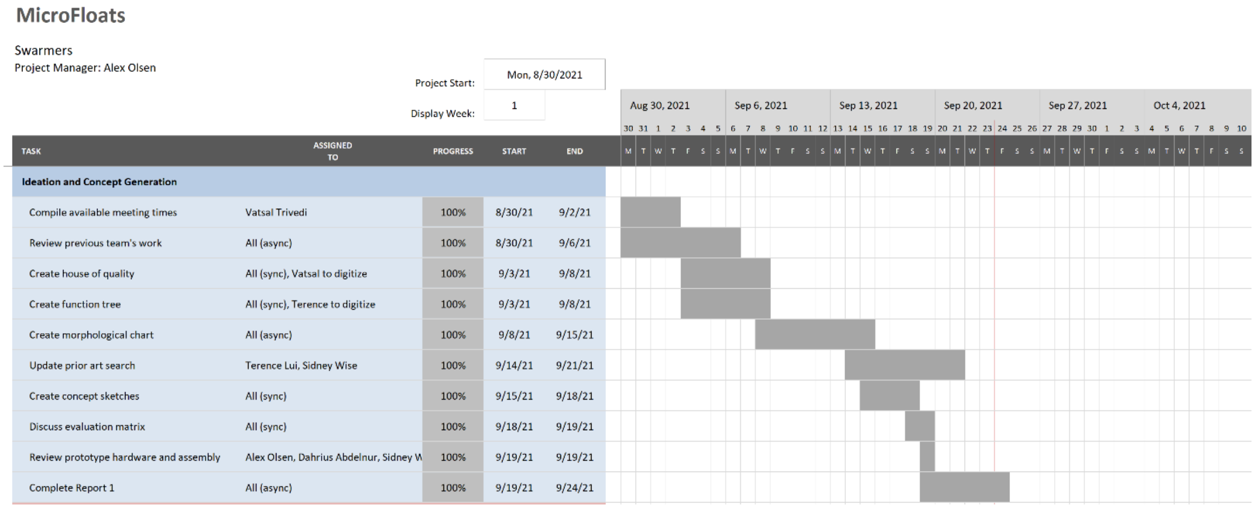
Appendix



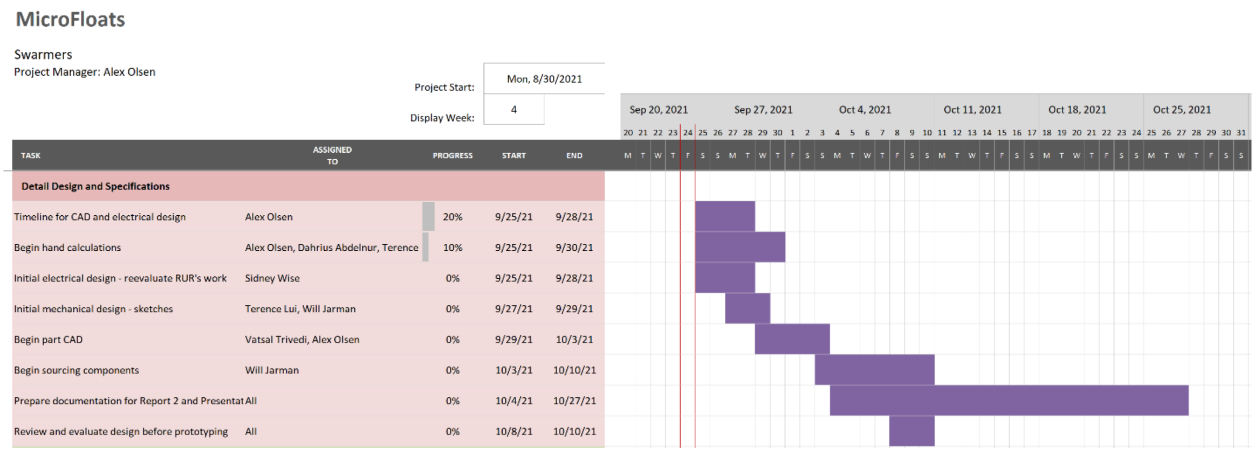


Figure 17. Gantt chart representing timeline for first nine weeks of the project.

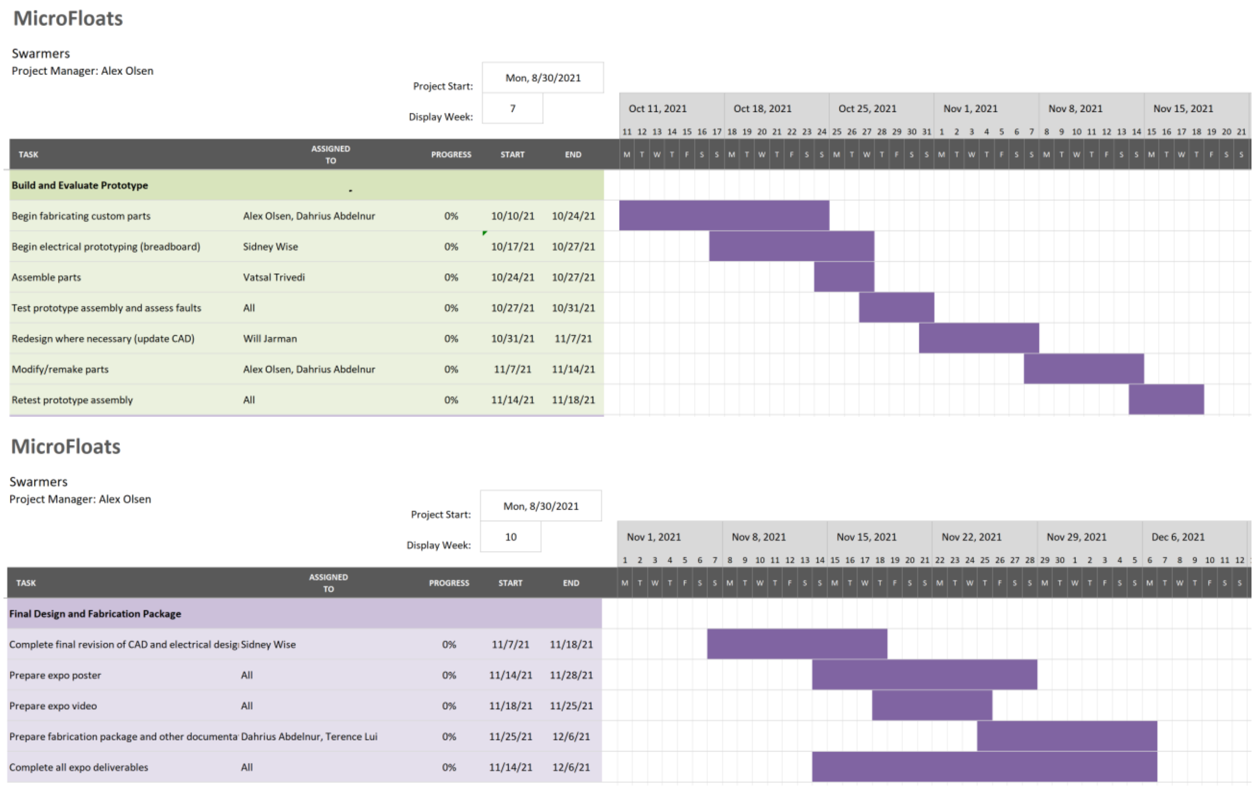


Figure 18. Gantt chart representing timeline for final eight weeks of the project.