ME 450

Winter 2026 Semester

FINAL REPORT

Finless Unmanned Underwater Vehicle Steering with Smart Morphable Skin

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Abstract

Unmanned underwater vehicles (UUVs) are essential for ocean monitoring, surveillance, and defense; however, traditional fins and rudders add drag, complicate packaging, and can be vulnerable to damage. Inspired by recent work in U-M's Experimental Fluid Dynamics Laboratory, this project pioneers UUV steering with a smart, morphable skin that actively changes its surface shape to generate control forces. We aim to design and build a finless, manufacturable, and water tight UUV hull prototype with morphing capabilities, then evaluate maneuvering performance in the towing tank at the Marine Hydrodynamics Laboratory.

Executive Summary

Current Unmanned Underwater Vehicles (UUVs) rely on traditional fins and rudders for control, which increase drag, complicate packaging, and introduce structural vulnerabilities. To address these limitations, Group 20 is tasked with designing and building a finless UUV prototype that utilizes a smart, morphable skin to generate steering forces. Sponsored by Dr. Anchal Sareen, this project aims to validate that asymmetric surface actuation (dimpling) can create sufficient sideways lift to maneuver (i.e. steer) the vehicle, thereby improving fuel efficiency and durability for future marine applications.

The design is inspired by golf ball aerodynamics, where dimpled surfaces delay flow separation and reduce drag through turbulent boundary layers. The project operates under the University of Michigan's IP policy, though the sponsor requires trade secret protection for the prototype. Stakeholder analysis identifies the Marine Hydrodynamics Laboratory (MHL) staff and the project sponsor as primary stakeholders, driving the following critical engineering specifications:

- Form Factor: A cylindrical body with a length between .25 and 0.75 meters and a length-to-diameter ratio of 7 to 14.
- Functionality: The skin must independently actuate dimples or pimples on port and starboard sides to a minimum depth of 0.01 inches.
- Durability & Safety: The device must be watertight, protecting electronics from shorting, and structurally stable at towing speeds up to 4 m/s.
- Constraints: The project must be completed within a $400 budget.

The primary challenges with the project are fitting a morphing skin tightly onto the submersible and designing a robust pressure management strategy. Furthermore, accurate validation of the model's functionality, its ability to form dimples, and its ability to collect meaningful data during final testing will be critical.

Research by the sponsor has confirmed the theoretical viability of the concept, supported by previous lab experiments where morphable spheres successfully generated lift in wind tunnels. The team is utilizing an iterative ME 450 design framework, having decomposed the prototype into four subsystems: internal skeleton, skin/dimples, actuation control, and watertight seals. The project is currently transitioning from concept generation to CAD modeling and component acquisition. Future phases will focus on assembly and preliminary waterproofing tests, culminating in final load-cell data collection at the MHL tow tank to verify steering performance.

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1.0 Introduction

The Finless Unmanned Underwater Vehicle (UUV) with Smart Morphable Skin is a project sponsored by Dr. Anchal Sareen. The objective is to explore a smart morphable skin mechanism that can be used to control UUVs [1]. Our group has been tasked with designing and testing a prototype capable of actuating dimples on either its port or starboard sides. Testing is to be conducted in the tow tank at the Marine Hydrodynamic Laboratory (MHL) to determine whether asymmetric dimpling can generate measurable turning forces, demonstrating the feasibility of this approach for future UUV applications.

Modern UUVs are used for ocean monitoring, surveillance, and defense by military, environmental, and commercial groups [2]. As the usage of these vehicles grows, improving fuel efficiency and decreasing material costs are important considerations. Conventional UUVs rely on fins and rudders for control, which increase material costs and drag, complicate packaging, decrease fuel efficiency, and require costly maintenance. Adding a dimpling morphable skin might mitigate these issues while maintaining efficient maneuverability.

Throughout the semester, our group will design and build a dimpled shell, morphable skin, and pressure regulation system capable of asymmetric actuation. The complete prototype will be tested in the MHL tow tank, where force data will be collected to validate the feasibility of the smart morphable skin steering concept. This project would be considered successful if the experimental results demonstrate the potential, or lack thereof, for sideways lift and drag effects to generate functional steering forces in future prototypes.

2.0 Background and Benchmarking

This project investigates a novel concept which uses dynamically morphable surface textures to create controllable aerodynamic or hydrodynamic forces. Since this specific implementation has never been tested before, there is limited research literature that directly applies to the topic. However, the fundamental fluid mechanics principles are well established and outlined in this section along with Dr. Sareen's active relevant research. Additionally, this section benchmarks industry exploration of surface morphing and its application to improved vehicle speeds.

2.1 Background

Inspiration for this project can be traced back to the design of the modern golf ball, a perfect example of aerodynamic optimization. Most would assume that a perfectly smooth ball would have superior aerodynamics to a dimpled ball, and thus would travel farther. However this is not the case, as the dimpled golf ball travels near two times the distance compared to that of the smooth ball. This improved performance can be traced to the behavior of the boundary layer; the layer of air that surrounds the ball as it travels through the air [3]. This performance can be seen visually in Figure 1, where a smooth ball's aerodynamics are compared to a dimpled ball [4]. The boundary layer of the smooth ball is fully laminar and becomes disconnected halfway across the

body. This causes a large area of low pressure that tails the ball causing drag. However, on the dimpled ball, the boundary layer remains connected to the body past the halfway point, leading to a smaller area of low pressure tailing, and therefore less drag. This is because the dimples of the ball each cause a small area of turbulence which attach to the boundary layer and allow it to continue along the body well past the halfway point.

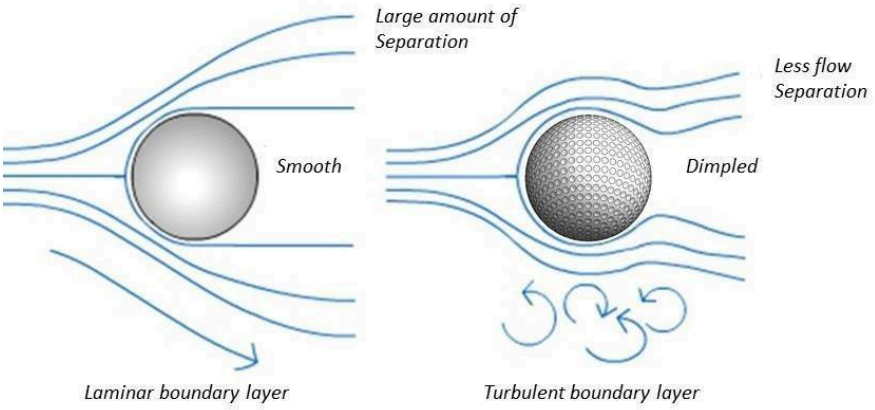


Figure 1. A diagram showing the turbulent/laminar boundary layer behavior of a smooth ball (left) vs a dimpled ball (right).

2.2 Prior Research

Using this understanding of the aerodynamic performance of the golf ball, one can now explore the work done on this project by Professor Sareen's lab. Her team has developed a small prototype, in Figure 2 [5], to test their theory of using malleable skin to steer an underwater vessel in place of traditional fins [5]. The prototype, a morphable sphere, can be broken down into two separate hemispheres, each with an internal skeleton that is individually wrapped with a malleable skin. The hemispheres are connected to an external vacuum that is controlled by an Arduino micro controller. The depth of the dimples on either side of the ball are the result of the connected vacuum sucking the air out of the ball, forcing the skin to retract around the skeleton [6].

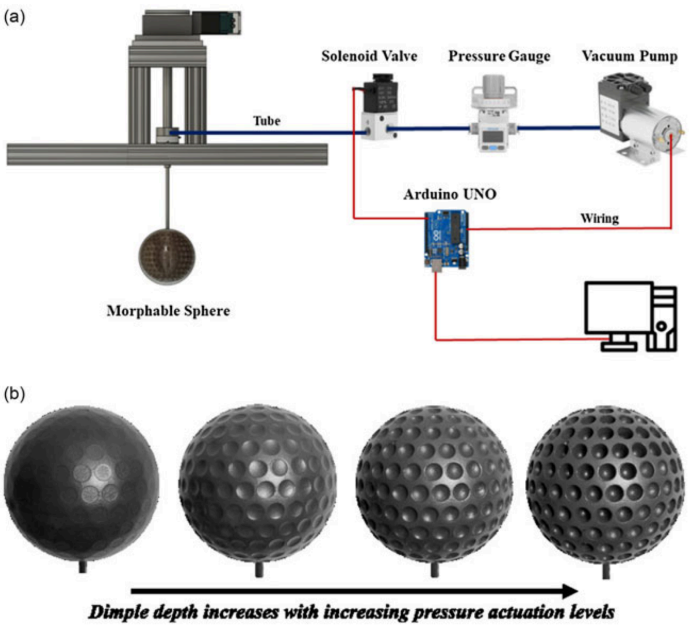


Figure 2. Diagram breaking down the experimental setup utilized in order to test the hypothesis of gaining controllable lift utilizing malleable skin.

The prototype was used in a controlled wind tunnel, where Professor Sareen's team was able to show that by controlling the individual hemispheres, they could create lift on either side of the ball [5]. Dimples would cause an aerodynamic tail, similar to that of a golf ball, which would result in the ball traveling in an arc in the direction of the dimples. This experiment can be seen in Figure 3 [7], where top dimples show a tail arcing down and bottom dimples show the opposite.

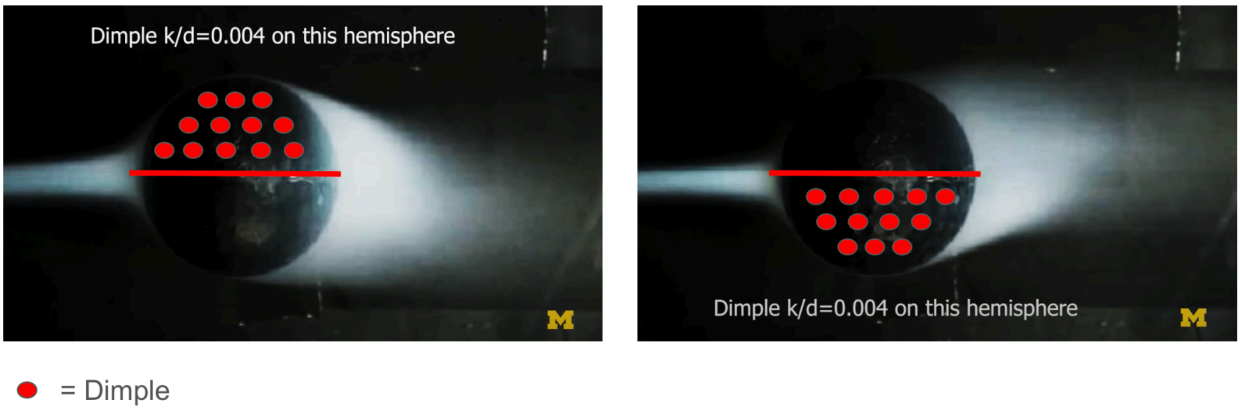


Figure 3. Results of wind tunnel testing of Professor Sareen's lab's prototype. The trailing tail of low pressure shows the ability to change the direction of lift through the changing of the surface texture.

2.3 Industry Benchmarking

The idea of using malleable surface features to steer a vehicle is a relatively new and unexplored concept [8]. This means the amount of information that can be gathered from industry benchmarking is very limited, with all of it coming from the automotive industry. The first of which can be seen in Mercedes Benz's Vision AVTR concept car [9]. This concept car is full of novel experimental features, one of them being an array of posable geometry on the tail of the car. This geometry shifts itself right or left in response to the car's desired direction in the aim of improving the aerodynamics of the vehicle. This concept was never delivered to a production car, but presents a theory similar to what our team aims to explore [10].

The closest example of Dr. Sareen's concept being used in industry can be seen in the Bugatti Bolide. The car features "pimples", seen in Figure 4, that expand or contract based on the desired turning direction and speed. While this is similar to the concept being explored in this project, these pimples are only found on a small area of the car known as the air scoop. This example does not use a malleable surface to steer the car, but rather complement the traditional steering taking place through the rotation of the wheels.

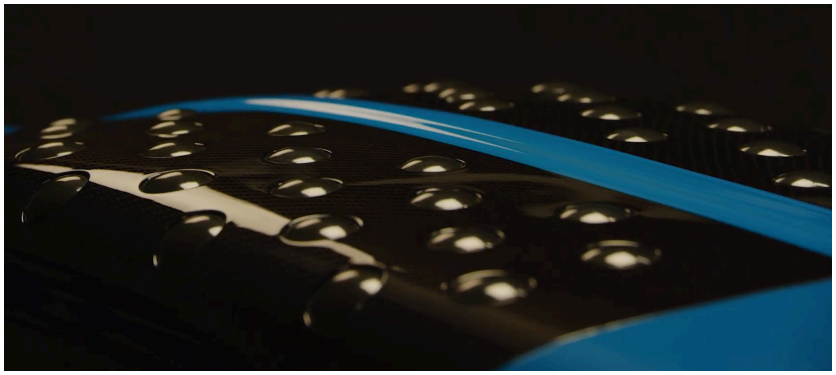


Figure 4 [11] Airscoop found on Bugatti's Bolide vehicle which features expanding and contracting pimples in order to optimize the aerodynamic performance of the car based on desired turning direction and speed.

Another source of inspiration to draw from is an experiment put together by the Mythbusters [12], which aimed to test the effect a completely golf ball textured surface would have on a car. While not directly aiming to steer the car, this experiment resulted in a 12% increase of fuel economy, demonstrating that the golf ball texture can have a major impact on the aerodynamic performance of a car. We can take this learning as a basis to show this specific texture can have an effect on the way a body carves through a medium, in our case water, in their case air.

3.0 Problem Domain Analysis and Reflection

The primary deliverable for this project is a prototype of a submersible body fitted with a morphing skin that is capable of being tested in the MHL tow tank, as well as the data collected from that testing. Additionally, we must deliver two additional test models, which do not contain

the morphable skin, but have either dimples or no dimples hard-built into a rigid model. This is included in our scope as both a control model in testing, and in case we must test earlier than our higher fidelity prototype is ready. Shown below in table 1 is some clarification on the scope of this project and what types of deliverables are and are not expected from this project. We believe this is an obtainable scope for us in our remaining time, and that we can deliver a prototype and complete testing before the end of the semester.

In Scope	**Out of Scope**
Designing and mounting morphable skin on a hull	Performing in-depth optimization and simulation of skin dimples
Designing independent port and starboard skin control	Any active vertical, pitch, or buoyancy control systems
Designing for compatibility and testing in the MHL tow tank	Designing an independent propulsion system
Designing a testable prototype and 2 backup/control test devices	Designing a market ready system
Generate data to evaluate if steering UUVs is feasible with this technology and guide future prototyping and development	Definitively prove that steering with morphable skin is effective, nor reach any specific torque or force metric with our prototype.

Table 1: A summary of key aspects of the scope of this project as it pertains to ME450, including clarifications of what is and is not in scope.

A fair number of our earliest concerns, especially those regarding the logistics and requirements for mounting and operating the device in the MHL towtank have since been alleviated. Of the major problems left to be solved, the two likely to be most challenging are sealing the device and selecting an appropriate skin. The sealing of the device concerns us, as there's so little room for error when making seals. We are developing processes to spot check our sealing and verify incrementally that we will have successful interfacing in smaller tanks, so we can be confident in our model once it is ready for full MHL testing. We are planning a series of empirical testing with several different samples of different types and thicknesses of elastomers to find a skin that provides the combination of stiffness and compliance, as well as sealability and durability that we require. We anticipate this to take a decent amount of testing in order to rigorously select the best sample available to us, and we require at least a decent amount of the assembled hull to do meaningful testing, so we must be careful to adhere to deadlines and give ourselves enough time for this stage. Beyond this, the most critical system for us to complete early and ensure it’s functionality will be the pressure system, as much of our future testing will be dependent upon its functionality.

The assistance of the MHL staff, who are specialized in operating devices in their underwater tow tank, will be a key technical resource when designing this device. It is important that we become familiar with any procedures and methods already in place to both ensure our goals are

met and to safely test the specifications. We also have access to people within the University of Michigan Naval Architecture and Marine Engineering (NA&ME) department with expertise with these types of issues that are available for consultation. Our only significant logistical concern is that we remain a lower priority for testing for the MHL towtank, and may not know the specific dates we must be ready for testing until we are closer to that deadline.

As of right now, our biggest information gap is in the performance of different types of skin. The plan to rectify this, as mentioned earlier, is to perform a series of empirical tests on different material samples to select the best available option. This testing can be performed as soon as we have a functional pressure system and a functional hull.

4.0 Design Process

Our team plans to follow the ME 450 Design Process framework, emphasizing problem definition, concept exploration, and solution development and verification. Key factors in successfully following this framework include demonstrating iterative design practices, maintaining strong stakeholder engagement, and taking the time to be reflective, considering the social, economic, and environmental impacts of the design.

Due to the complexity of the project, a linear design process would not be the most effective way to approach the problem. For our problem, an iterative approach allows for greater design refinement, such as optimization of the dimensions of the skeleton and dimples on our prototype. Like the ME 450 framework, it is important for our team to maintain an exploratory mindset, focusing on the convergence and divergence of ideas which might include changing the placement or ratio of dimples on the skeleton. An example of a complex, iterative design process is demonstrated in figure 5 below.

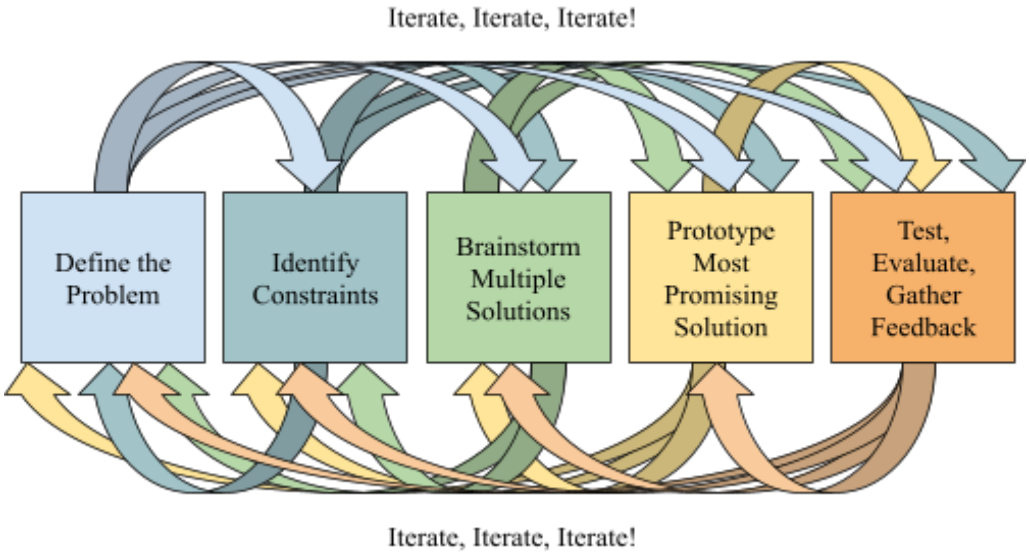


Figure 5. Iterative design process graphic which demonstrates that iteration can occur at any stage of the process.

In our preliminary design review, we focused heavily on problem decomposition to ensure that our objectives for the semester are attainable. The prototype was broken into the following subsystems: an internal skeleton, which must have optimal dimensions and a watertight integrity; the skin and dimples, for we need to determine the appropriate size, depth, and spacing; the actuation control system, which after extensive discussion with our sponsor and the MHL staff, will be off-board and easily controllable; and the skin and watertight seals need to withstand the hydrostatic pressure fluctuations in the tow tank.

Currently, we are at the phase titled “prototype most promising solution”. Our team is developing a bill of materials and a preliminary CAD model of the design to present to our sponsors. This model will be discussed further into this report. Depending on stakeholder feedback, our team may need to turn back to the brainstorming stage before manufacturing, assembling, and testing the prototype.

5.0 Stakeholder and Design Context

This section evaluates the broader social, economic, environmental, and professional contexts surrounding the morphable skin UUV project. Project success relies on careful consideration of those who are affected by this project in the short term, involved in the decision making process, and might be affected by the results of this project in the future. The following subsections outline the project’s key stakeholders, their influence on the project, any associated ethical considerations, sustainability impacts, and the intellectual property responsibilities of the project.

5.1 Stakeholder Identification

The design and testing of the morphable skin prototype involves a variety of stakeholders with different engagement and impact levels. Primary stakeholders include our project sponsor, the Marine Hydrodynamics Lab staff, marine researchers, and naval engineers. These stakeholders are directly responsible for integrating and testing the prototype to determine if finless steering is possible. Secondary and tertiary stakeholders include the U.S. Navy, materials suppliers, equipment operators, other underwater vehicle manufacturing groups, environmental protection groups, sports engineering researchers, and marine life. These groups may be indirectly affected by the project through future implementation of the technology we are developing, or through the use and disposal of the material used in this project.

The stakeholders that are directly involved in the design and testing of this prototype are the ones who can benefit most from the success of the project. Our team gains hands-on experience, expanding our technical knowledge for future design tasks. Additionally, Professor Sareen and her colleagues gain valuable information about the limitations of this technology, allowing for it to be applied to more complex and impactful systems in the future. Indirectly affected stakeholders include policy makers, environmental groups, and marine life, as they may experience minor impacts as a result of energy consumption, materials disposal, and testing activities.

Our team has created a preliminary list of stakeholders, organizing them into the stakeholder map in figure 6 below. and will be developed and modified as the project progresses.

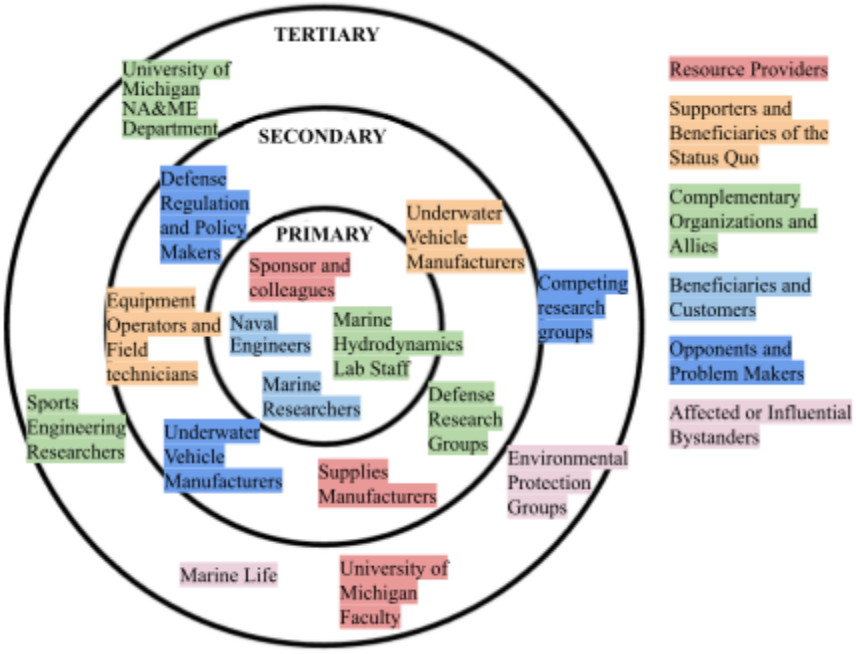


Figure 6. Stakeholder map categorizing stakeholders by ranking (primary, secondary, tertiary) and type (color-coded). Some stakeholders fall into multiple categories which may result in multiple rankings.

5.2 Stakeholder Influence and Engagement

While stakeholders like Dr. Sareen and the MHL staff will have some influence in the project design, our team is solely responsible for determining the final prototype design. We aim to mitigate any power imbalance between our team and primary stakeholders engaging in regular meetings to determine best practices about designing a prototype for the towing tank. We are scheduled to meet with Dr. Sareen every other Friday, and the MHL engineering team weekly on Tuesday afternoons.

5.3 Ethical Considerations

The greatest ethical issue facing this project is about the end use-case of this technology. While UUVs are used in environmental and commercial purposes, they are mostly used in the military. If our team is able to successfully demonstrate that the morphable skin technology can generate enough side force for steering, the data will be used as evidence to apply for funding from the US Navy to design a UUV suitable for military use. Supporting a design intended for the delivery of weaponry to the military conflicts with the personal morals of some team members, creating an ethical concern. Reconciling this, this research only focuses on the feasibility of the

turning mechanism which would hopefully decrease the production costs of UUVs, making them accessible to smaller environmental or commercial groups.

5.4 Sustainability and Environmental Impact

Through preliminary eco-auditing using Granta EduPack, our project is extremely sustainable considering that it only needs to be used a small handful time and will comprise mostly of recyclable components (PLA, latex, electrical components). The main contributor to its unsustainability is that some electrical components may not be recycled. To solve this issue, when the prototype is disassembled, the electrical components can be reused by Dr. Sareen's Experimental Fluid Dynamics Laboratory so long as they are not damaged in testing.

5.5 Intellectual Property and Confidentiality

Our project does not require a Non-Disclosure Agreement (NDA) or Intellectual Property (IP) transfer, meaning that the University of Michigan's IP policy will be in effect. As students doing work on a research project at the University, the work that we do on the project will remain our own. Our sponsor will be able to use our work since it is a part of a larger research initiative, and will keep the prototype. However, our sponsor has asked us to keep this investigation at a trade secrets level which must be respected, especially when discussing with other professors or organizations.

6.0 User Requirements and Engineering Specifications

Described below in Table 2 is a list of the all stakeholder requirements we have identified, of which there are 12, and their associated specification(s), of which there are 15. Each requirement is given an ID number, by which it will be referred to later in this report for brevity. It is also assigned a classification identifying it as foundational, testing, operational, or miscellaneous. Foundational requirements define what the device must be in order to accomplish the base goals of its purpose; testing requirements define what the device must be to be able to sufficiently and safely test it in the MHL facility; operational requirements define which are things the primary device must be able to do or withstand as part of quality operation, but does not necessarily fall under a requirement for the foundational nature of the device or requirements of the device to test in the MHL tow tank; and miscellaneous is assigned to requirements which do not translate directly into the form or function of the device, but are considered necessary for the project's success. Additionally, a priority is assigned to describe how essential the requirements are to the project being successful. These priorities are based on stakeholder influence, requirement flexibility, and general impact on project success. For example, not meeting a high priority requirement could be catastrophic, but not meeting a low priority requirement, while suboptimal, would not derail the entire project.

ID #	Classification	Priority	Requirement	Specification(s)
1	Foundational	High	The device must be able to form pimples or dimples on its skin while underwater	The controlled device must be able to form either concave protrusions of a depth at least .01” at the vertex
2	Foundational	High	The device must be able to test whether aquatic steering is possible with this technology	The controlled device must have at least 2 independent sides of actuation (port/starboard)
3	Foundational	High	The device must roughly mimic the shape of an average unmanned underwater vehicle	The controlled main body of the device must have a primarily streamlined body with a length/diameter ratio between 7 and 14
4	Foundational	Mid	The device must be a feasible but still large enough scale to achieve Reynolds number similarity to previous experiments	The device must be between 0.25 and 0.75 meters in length
5	Testing	High	The device must be safe to submerge for testing	Any onboard electronic devices must be protected in a way that is waterproof, such that there is no shorting in the water, 0 current and no resistance from the electrical system is detectable in the water and no functionality is lost The submerged portion of the device must not contain components that would dissolve, deform, or otherwise be damaged by water or by contact with water, release pollutants
6	Testing	High	The device must be tested in the MHL tow tank	The device must be structurally stable to test at speeds up to 4 m/s while underwater. The device may have a cross section no greater than 0.5m x 1m at any point The device must use mounting hardware compatible with the MHL tow tank load cell
7	Testing	Mid	The device should be durable enough for several days of testing in the MHL test tank	The device must be able to withstand at least 25 test runs
8	Operational	Low	The device shouldn’t consume large amounts of power	The device should need no more than 1000W at peak to operate
9	Operational	High	Dimples/pimples shouldn’t actuate just because of local pressure differences	The device must operate using pressures at least an order of magnitude different (10x) than those at test depth & dynamic pressure: [A positive pressure system must achieve at least 49 Psi and a negative pressure system at least -13 Psi]

10	Operational	High	Skin must not puncture as a result of normal operation	Skin must be able to withstand 100 kpa of relative pressure without breaching
11	Misc	Mid	The project shouldn't cost much to carry out	The project has a budget of $400
12	Misc	Mid	2 static backup devices with no actuation must be produced in case testing must be moved up	A 3D printed dimple-less hull and a 3D printed hull with dimpling patterns as described on one side must be produced as a contingency

Table 2: A summary of stakeholder requirements and engineering requirements, ordered with an ID number, a classification, and a priority for each requirement.

These requirements were primarily derived in discussion with Dr. Sareen and the MHL staff. Given that this project is an extension of research, these primary stakeholders had valuable input on the specific thresholds needed for the engineering specifications. Specifically, the specifications for requirements 2, 4, 9, 1, and 12 come directly from Prof. Sareen [15, 16], while those for requirements 5 and 6 were provided by MHL staff [15].

The remaining specifications for the outlined requirements were established by benchmarking analysis and outlined as follows; Requirement 1 is benchmarked against the dimple depth golf balls used to get aerodynamic effects, although we set this as a minimum since this is a dynamically controllable system [16]. Requirement 3 is benchmarked against the range of aspect ratios of submarines designed by major countries currently in service [17]. Requirement 7 & 8 are estimates based on what we understand of the project goals. While not explicitly outlined by numerical targets, they fall within a range broadly described by our sponsor and match approximately with what similar scale and type of appliances endure. Requirement 10 was determined with a quick calculation of the expected static pressure of being submerged at the bottom of the tow tank (34 kpa) and adding a safety factor of 3 [18]. Notice that specifications on the turning torque, drag force, or other hydrodynamic effects are not listed as specifications or requirements, as the purpose of this project is to test whether maneuverability forces are even possible. Dr. Sareen has not set a required threshold, goal, or target measurement, but to measure the potential effects of the technology in this form factor and get data to support whether the use case for this technology is sensible.

In terms of standards we must meet, this is not a market-going device, and is only a prototype used to further research. The only essential specifications are those outlined for the use of the MHL towtank, of which the key points have been described above, without going into the fine detail of mounting hardware.

All the above requirements and specifications above are both complete and reasonable to the best of our knowledge. Should all these requirements be met, we believe we will produce a project that will meet our goal and the goals of our primary stakeholders.

7.0 Concept Generation

Our preliminary concept generation phase helped turn the broadly scoped problem and varying requirements and specifications into approachable subsystem solutions. Unlike many open-ended product design tasks, this project operates within clearly defined constraints established by the sponsor. The primary objective is to experimentally validate the theory that finless steering is possible rather than design an autonomous, field-ready vehicle. As a result, the prototype was required to remain a streamlined body, consistent with traditional UUV geometries.

Additionally, the design needed to remain scientifically consistent with the prior and current research conducted by Dr. Sareen and her graduate students to ensure continuity with her ongoing work. Applying a variety of simple ideation methods gave the team an opportunity to explore both the obviously feasible as well as more outlandish concepts, while still staying within the bounds of Dr. Sareen's research.

7.1 Preliminary Methods

Our team's concept generation process began with independent brainstorming. Each team member developed a minimum of 10 concepts individually. This approach encouraged diverse thinking, reduced fixation, and ensured that no single idea dominated in the early generation phase. These initial concepts are outlined in Appendix A (Figures A1-A4).

Following the initial ideation phase, each team member applied additional concept generation strategies to iterate on these concepts, expanding and refining their ideas. This iterative process ultimately resulted in a total of 20 concepts per team member, shown in Appendix A (Figures A5-A8).

Together, the team conducted a collaborative mind-mapping session. This method allowed for all members to propose a variety of concepts without premature evaluation and explore connections between concepts manageably. The visual structure of the mind map encourages expansion in multiple promising directions while avoiding fixation. The completed mind map is shown in Appendix A (Figure A9).

Additionally, the team performed a group morphological analysis which aimed to focus on the primary subsystems of hull shape, skin and dimple, and pressure system concepts. While this helped our team to offload some of the ideas that we had been holding on to, this morphological chart was generally unsuccessful as our ideas were not mutually exclusive for each parameter. Some of these ideas inspired further concept generation, so it has been included in Appendix A (Figure A10).

7.2 Subsystem Identification

The team mind-mapping session helped to identify key subsystems within the overall problem scope. These subsystems were defined as the hull, dimples, skin, pressure actuation system, and

testing configuration. After further discussion, our team agreed that testing configuration primarily falls under the scope of requirements and specifications planning rather than concept generation. Similarly, the skin subsystem offered limited conceptual creativity and variation aside from material selection and fastening strategy. Therefore, we focused concept generation on the other three subsystems.

7.2.1 Hull

Given the design requirement that the device must roughly mimic the shape of a conventional UUV, our team identified four typical streamlined geometries which could serve as a baseline for the hull concepts. These ideas are summarized in the morphological chart, Table 3, below.

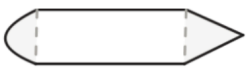
Hull Shape	Side View  Front View 	Side View  Front View 	Side View  Front View 	Side View  Front View 
Concept Description	***Football Hull*** Elongated football or pool torpedo shape. Conical nose and tail, gradually increase in radius until meeting in the middle	***Ice Cream Hull*** Conical body with hemispherical nose	***Cylindrical Hull*** Cylindrical body with a hemispherical nose and conical tail. Maybe modular to make testing other shapes possible.	***Fish Hull*** Fish shaped meaning that the body is taller than it is wide. Make shape more similar to flat plane experiment.

Table 3: The morphological chart for hull shape.

The *Football Hull* was influenced by the shape of a children's diving torpedo, resembling a prolate spheroid with pointed ends. This geometry would theoretically minimize drag due to its continuously varying curvature.

The *Cylindrical Hull* model was inspired by commercially available UUVs such as the EcoMapper Nano [19], pictured in figure 7.



Figure 7. EcoMapper Nano used as inspiration for the *Cylindrical Hull* hull shape concept.

The EcoMapper Nano consists of a cylindrical midsection with a hemispherical nose and a conical tail. This configuration provides simplicity and allows for easy modulation and skin attachment.

The *Ice Cream Hull* consists of a hemispherical nose which transitions into a conical body. This geometry combines some of the characteristics of the *Football* and *Cylindrical* concepts, but would be simpler to manufacture than the *Football.*

The *Fish Hull* draws inspiration from biological streamlining, aiming to leverage the natural hydrodynamic efficiency of a fish. While not necessarily traditional to the shape of a modern UUV, the shape might be successful in creating side forces that could be used for turning.

7.2.2 Dimples

The dimples subsystem was divided into two primary design components; dimple geometry and dimple location. Dimple geometry includes parameters such as shape, diameter, depth, and spatial density. Based on the research conducted by Dr. Sareen's graduate students, a baseline for dimple size and depth has been provided as a starting point [20]. However, previous work focused on spherical and flat plane geometries rather than fully streamlined bodies. Therefore, the interaction between distributed dimples and the hull curvature remains an open ended question. For this reason, concept generation focused on both dimple shape and placement. These variations are summarized in Table 4.

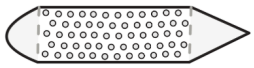
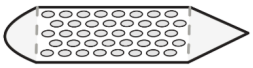
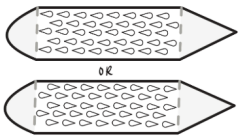
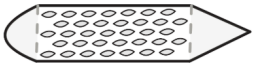
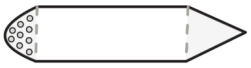
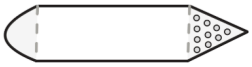
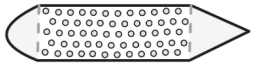
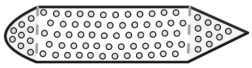
Dimple Shape				
Concept Description	***Round***	***Oval***	***Teardrop***	***Football***
Dimple Location				
Concept Description	***Nose only***	***Tail only***	***Center body only***	***Full coverage***

Table 4: The morphological chart for dimple shape and location.

Possible dimple shapes included round, oval, teardrop, and football. Each of these shapes minimize sharp corners, reducing the risk of tearing the skin material that is laid over top. The dimple geometry and location will directly influence the boundary layer transition and separation, so they play a critical role in determining the feasibility of finless steering. These options included on the nose only, tail only, center body only, and uniform full coverage.

7.2.3 Pressure Actuation

The pressure actuation subsystem controls how dimples are activated. The main requirement of this subsystem is that it must provide controlled, repeatable pressure differentials. Initially, the sponsor had also added that the system needed to be compact enough to be fully internal to reflect realistic UUV implementation. However, during early concept development and feasibility discussions, it became clear that integrating this kind of system would increase design complexity and risk as it would have to be compact, sealed, and remotely operable. Any small errors would risk the integrity of the electronic components, delay the project timeline, and could ultimately lead to project failure.

After reviewing these concerns, Dr. Sareen agreed that for the purpose of experimental validation, we could consider offboarding the system. The strongest concepts we developed are summarized in table 5, below.

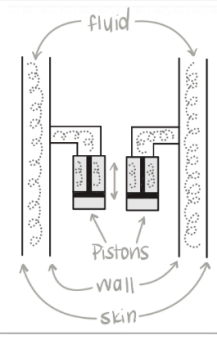
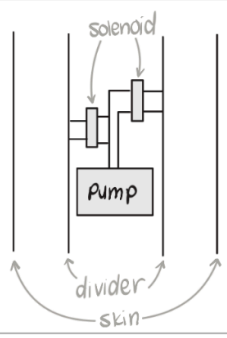
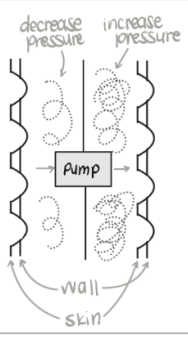
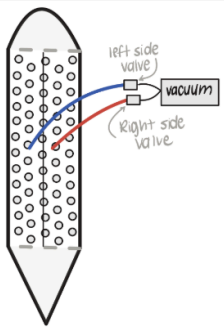
Pressure System				
Concept Description	***Fluid Method*** Actuate skin by pressing in a fluid to the chamber between it and the wall	***3 Pressure Chambers*** Pump in a third chamber to independently control right and left side with solenoids (3 pressure chamber)	***Pimples and Dimples*** Push air from one half to the other. This would actuate dimples on one side and pimples on the other.	***2 Pressure Chambers*** Offboard electronic components and run air into left or right side (2 pressure chamber)

Table 5: The morphological chart for the pressure actuation system.

The *Fluid Method* uses pistons to push fluid in and out of the cavity between the skin and hull to actuate dimples. Using a fluid in the system instead of air might reduce buoyancy and unwanted dimpling from hydrostatic pressure.

The *3 Pressure Chambers* method uses a third internal chamber to independently control either side of the vessel using solenoids.

The *Pimples and Dimples* method pulls air out of one side of the vessel, actuating dimples on that side. The air is then pushed into the opposite side, actuating pimples. This method would be slightly more complex, requiring the skin to be sandwiched between two hull layers so that the pimples and dimples could be reversible on both sides.

The *2 Pressure Chambers* method applies the grace of offboarding the electronic components. Each side would be independently connected to a vacuum with switches or valves on the tubes so that the vacuum could be activated independently on either side.

7.3 Concept Expansion

Following subsystem identification and baseline concept development, the team explored design heuristics to expand and refine the configurations previously developed. Rather than generating new subsystems or concepts, this phase focused on modifying the existing ideas to improve modularity and manufacturability.

7.3.1 Modularity and Interchangability

Our team was inspired by design heuristics card 42: Make components attachable/detachable. This led the team to explore the idea of modularizing the hull which could help increase

experimental flexibility. Specifically, the nose and tail sections could be designed as interchangeable components that could be detached and replaced independently of the main body.

A modular approach would enable rapid testing of multiple geometries, reduce manufacturing time by reusing the midsection, and allow for incremental iteration without redesigning the full body.

Part modularity means that hull components would need to connect and disconnect. Our team was further inspired by design heuristics cards 66, twist, and 57, rotate, which sparked the ideas of using threaded components or a twist lock mechanism. Card 18, allowing users to reorient, inspired the idea to use magnets which would give parts a defined polarity for assembly and packaging simplicity.

7.3.2 Various Attachment Methods for Skin

To expand on the subsystem concepts, our team used semantic variation by generating synonyms for “attach”. This method encouraged broader thinking about how the skin could interface with the hull. Attachment concepts considered included tape, glue or adhesive bonding, hook-and-loop, snap-fit features, screw-fastened panels, and wrap based tensioning. This method of using design heuristics allowed our team to consider unconventional approaches to a seemingly simple issue.

8.0 Concept Selection Process

The primary tool used by our team in the concept selection process is a decision matrix. A decision matrix operates similarly to a Pugh chart, with weighted categories that you compare different designs across, however instead of setting one of the designs as a baseline and ranking each design +1 or -1 from the baseline in each category, you score each design from 1 to 10 in the category. This method allows us to more effectively compare different designs to each other without needing a common baseline, and also allows us to better discriminate between the degrees to which some concepts are better than others in certain regards [21]. This gives us a fairly high degree of confidence that while some concepts that were not selected have certain advantages over the ones that were, the selected concepts are the best for our use case. It is also of note that the categories selected may not translate directly into the verbiage of the design requirements, but all the categories were selected in such a way that describes the methodology by which the specific subsystem would fulfill a given requirement. For example, “compatibility with common UUV architectures” may not seem to directly translate to a requirement, but is a method by which requirement 3, modeling a UUV's shape and form factor, can be met. All the categories we are judging designs by have been selected to follow this pattern of describing the specific means by which any given subsystem would fulfill our requirements.

As described above in the concept generation section, our design can be broken down into a number of subsystems, almost all of which would be compatible with any other solution from a different subsystem. The subsystems we need to do in-depth analysis on are the hull shape, the dimple shape, the dimple placement, and the actuation system. The clear distinction between these systems affords us some modularity, giving us the freedom to select the best option for each subsystem and then combine them into one singular design concept, which will be described in greater detail in the following section. In fact, by analyzing four different morph charts each containing 4 designs, and combining them modularly, we are selecting the best of 256 possible designs.

8.1 Hull Selection

Shown below in Table 6 is our decision matrix for the shape of the hull. There are 5 categories used to judge these designs: the simplicity of watersealing the design, the complexity of the manufacturing methods necessary to make the shape, the modularity of the design, or difficulty to change and iterate on individual parts, the resemblance of the shape to common UUV architectures, and how well the body is streamlined. The most important of these categories, with regards to the hull, is how well it mimics a UUV shape, reflected in its weighting, with the modularity being of relatively low importance as it exists to make the design process less expensive. All the others fall in between.

Category	Weight	Football Hull	Ice Cream Hull	Cylindrical hull	Fish Hull
Simplicity to water Seal	x2	8	8	6	3
Simplicity of Manufacturing	x2	5	6	7	4
Modularity	x1	2	5	8	2
Resemblance to used UUV body shape	x3	5	5	9	2
Streamlining quality	x2	8	8	8	6
Total	/100	59	64	77	34

Table 6: The decision matrix used to decide the shape of the hull. The matrix selects a cylindrical hull with a score of 77, and has a maximum possible score of 100

Ultimately, the best design we selected here was the cylindrical hull with a score of 77. The likely deciding factor here was that, compared to the other body shapes, this one bears significantly more resemblance to the majority of UUV architectures [22]. Some of the other shapes are used in niche designs, but most research and military vessels use this shape. This

design also provides more available modularity than all other designs, with a distinct front and rear that can be iterated, as well as the cylindrical profile more readily lending itself to FDM 3D printing than other shapes. Because there are more distinct profiles, however, there is potential for this design to be harder to seal against water intrusion than some other designs, and it's comparable in terms of boundary layer separation uniformity to the other frontrunning designs, which is why this design wasn't a runaway winner.

8.2 Dimple Shape Selection

Similarly, shown below in table 7 is the decision matrix used to analyze the shape of the dimples. The categories here are alignment with the previous body of research of our sponsor on this topic, the simplicity of manufacturing these shapes, and the risk of the skin being punctured added to the design by the shape of dimples. Of these, by far the most important is to put out something that is useful to the research of our sponsor. The risk averseness of puncture is a consideration that is mostly controlled with the material of our skin, which is why it is given the lower ranking along with manufacturability.

Category	Weight	Round	Oval	Teardrop	Football
Alignment with previous research	x3	10	4	2	2
Simplicity of Manufacturing	x1	8	6	4	4
Risk averseness to skin system	x1	6	5	2	2
Total	/50	44	23	12	12

Table 7: The decision matrix used to decide the dimple shape. The matrix selects round dimples with a score of 44, and has a maximum possible score of 50

Round holes were a very clear winner for us here because Prof. Sareen's research has focused almost exclusively on round-shaped dimples, and we want to stay as relevant to her body of research as possible. Doing this also allows us to scale the size of the dimples accurately to achieve Reynolds number similarity with experiments that some of her graduate students have recently performed on flat plates that provide promising results [20]. It also helps the case for round dimples that the round holes are the simplest to manufacture due to their symmetry and that they lack any sharp edges that could be stress concentrators on the skin, boosting its score in the other two categories [23].

8.2 Dimple Coverage Selection

Shown below in table 8 is the decision matrix for the placement of the dimples, or their overall coverage, with the category of compatibility with common UUV architectures being the most important, followed by how effective we anticipate a given solution would be at generating hydrodynamic forces, and lastly, manufacturability. We weigh the compatibility with UUV architecture so high because if we generate a solution that couldn't actually be used in a real vehicle, because it gets in the way of some function, then it has no value in the future market. Similarly, the next highest consideration is anticipated effects, as we want to give as much chance of success to the device as possible.

Category	Weight	Nose	Tail	Center	Full Body
Compatibility with common UUV architectures	x3	3	3	8	1
Simplicity of Manufacturing	x1	3	4	8	1
Anticipated Hydrodynamic Effects	x2	8	3	6	10
Total	/60	28	19	44	24

Table 8: The decision matrix used to decide the dimple coverage and placement. The matrix selects covering the center with a score of 44, and has a maximum possible score of 60

We had a fairly clear winner for the middle here, with the dominating factor being the compatibility with UUV architectures. Most UUVs have instrumentation and often cameras at the nose, and a prop on the tail, which makes coating in those areas impractical, leading to the significantly higher score of body only. The center-only option also makes fitting a skin significantly easier, as the geometry allows for a simpler wrap of the skin. The center likely wouldn't experience the same level of hydrodynamic effects as the nose, since the effects we are looking for are based upon boundary layer separation and the transition to turbulent flow. However, we do anticipate the turbulent transition will occur well within the center body, and we would still be able to see the types of effects we're looking for without covering the nose. This flow separation distance is also why the tail scores so low, as the flow should already be turbulent at that point [24].

8.4 Actuation System Selection

The final decision matrix, table 9 below, will analyze the options for the actuation system of the dimples. Here, by far our most important factor is the ability to generate significant enough pressure to actuate the system. The complexity of the system is weighted heavily, as it potentially

needs to be operated by technicians unfamiliar with the system, as well as being maintainable over several tests. The risk posed to the system if water were to breach was also a decent consideration. The ability to independently actuate port and starboard sides is also considered; however, it isn't weighted as high since all these systems are capable of this, it's just a measure of the degree of interdependence between the sides in the pressure system architecture. Cost is weighted here because we anticipate this system to be the primary driver of our material costs.

Category	Weight	Fluid Method	3 pressure chambers	Pimples and dimples	2 pressure chambers
Ability to generate pressure differences	x3	9	6	5	7
Complexity	x2	2	4	5	9
Cost	x1	3	6	6	9
Risk averseness from water breach	x2	6	3	2	10
Independence of port and starboard actuation	x1	10	7	3	10
Total	/90	56	45	38	78

Table 9: The decision matrix used to decide the dimple actuation method. The matrix selects the 2 pressure chamber concept with a score of 78, and has a maximum possible score of 90

Here, the 2 pressure chamber system was selected, with the likely determining factor being the risk posed to the system by a water breach. This system involves offboarding all electronic components, which significantly drops the potential damage caused by a breach, leading to it's high score in that category. It did score slightly lower than the fluid method in generating pressure, as an incompressible fluid does have some noticeable advantages over pneumatic vacuum systems, notability a higher pressure range and a more strict dependence on position, even if both are capable of achieving near true vacuum [25]. The 2 pressure chamber system is also likely helped by being by far the simplest of the solutions, with no onboard communication or digital control being necessary. It also features, in general, cheaper and fewer components than the other systems, driving its winning score in cost.

8.5 Skin and Mounting Component Selections

We did not perform this style of morph chart analysis for selecting the skin type, as we plan to acquire several samples of different materials and thicknesses and perform some empirical testing to find the best match between stiffness, formability, and attachment. This part of the system is fairly modular, which allows us to perform this type of testing without a major redesign

required based on our results. Similarly, attachment methods were not analyzed this way, as this system is designed in coordination with MHL staff and based upon their existing equipment and infrastructure, and there are relatively few design variations for us to analyze.

8.6 Growth in Ideation from Initial Designs

The initial solutions our team generated were quite different from what we have landed on, or even the ideas present in initial concept generation. Some of our initial ideas were much more complex than our current options. For example, we initially assumed we would be putting two vacuum pumps in the submarine itself. We also initially had ideas about thermoforming our skin onto the shape of our device, or even designing the device to have both an endo and an indo skeleton. These initial designs were a lot more difficult to execute, more expensive, and, upon further analysis, sometimes even out of our scope when compared to our present ideas. Because of the broad changes our design has undergone throughout our ideation and design process, we see minimal elements of fixation, and that which we do see, we can identify as being part of trying to stay relevant to our sponsor's research and to stay compatible with the wider use cases of UUV.

9.0 Selected Concept - Alpha Design

The first concept selected through our rigorous selection process was the shape of the UUV's hull, that being a cylindrical shape. The hull will also be the location for the UUV's circular shaped dimples. With this in mind we moved forward with our alpha design concept. This hull design can be seen in figure 8, where the hull is also shown separated into two separate chambers. This was also part of our concept selection process, where our group settled on a design featuring two separately controlled actuating sides to the UUV.

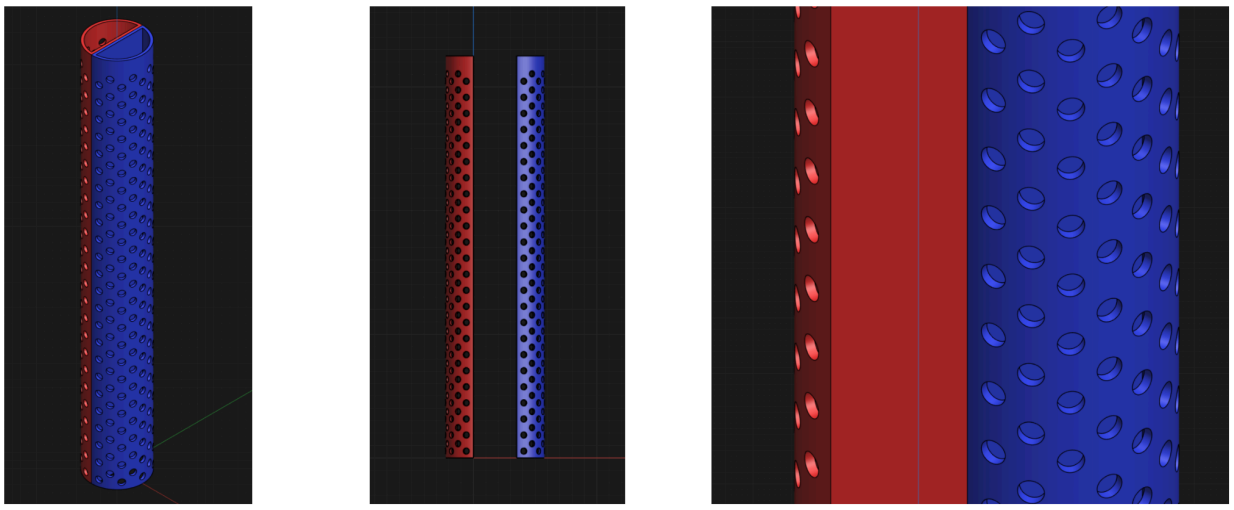


Figure 8. The hull design for our alpha concept. This design features a cylindrical shape, circular holes for dimples and a 2 sided pressure system.

Our sponsor also gave us direction for how to design the ends of UUV. They requested we make the front tip a spherical shape and the rear tip conical. These requests very closely resemble the shape of traditional UUVs, this means our testing will be directly applicable to the industry standard shape of modern UUVs. The entire design we made with these requests can be seen below in figure 9.

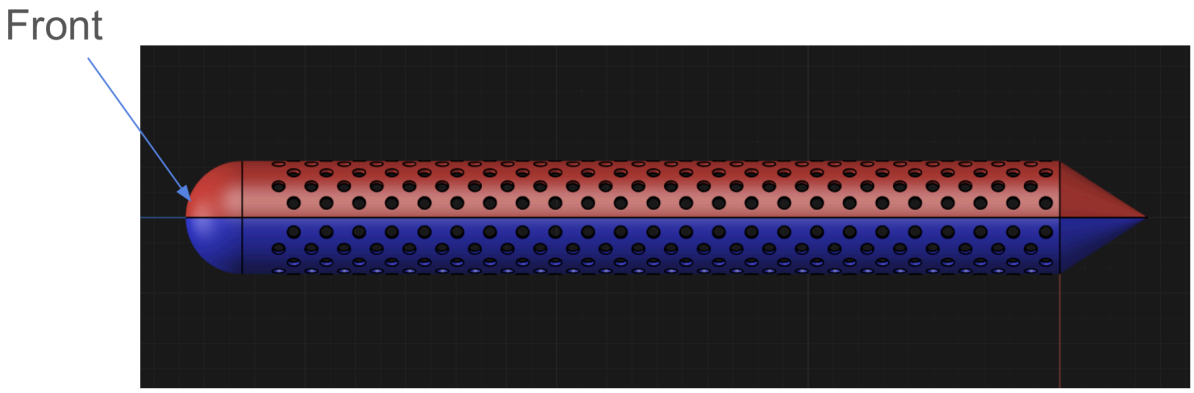


Figure 9. The full design of our alpha concept, including the sponsors requested features of a cylindrical front and conical rear.

This design reflects our requirements given to us by our sponsor as well as the research we individually did to look into the industry standards regarding a vehicle like this. As far as testing is concerned, we have also laid out a very early concept of how we anticipate to complete our testing in the MHL. As seen in figure 10, we plan on using a vacuum pump to control/actuate the dimples on the UUV. We plan to place the vacuum on the carriage and connect it to the UUV using a T-splitter with a controllable valve on each side. When a valve is open, it will create a vacuum in the connected half of the hull. While if the valve is closed, there will be no present vacuum and the hull will function as a smooth, “regular” hull, as the vacuum pressure system will feature an ambient air pressure release. Downstream from these valves there will also be a pressure gauge to measure the precise amount of pressure in the submersed body.

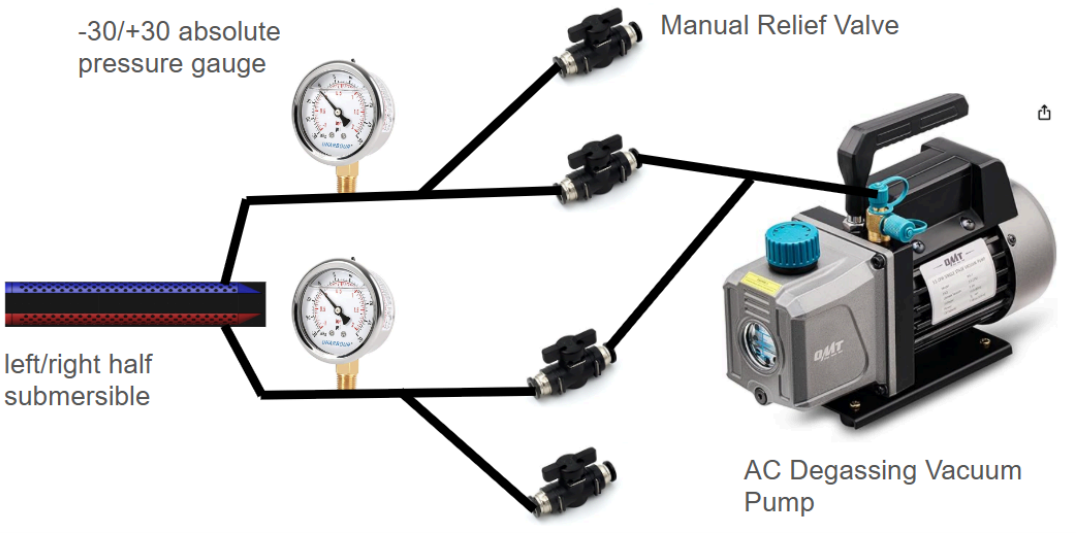


Figure 10. Our anticipated pressure system setup, involving the UUV's two independent halves each connected to a vacuum to control the dimples.

10.0 Initial Problem Analysis and Iteration

This project has a wide variety of requirements, each requiring a development or refinement of particular skills in order to validate. Our team must become familiar with certain fields of off-the-shelf components. This includes vacuums, valves, tubing, for the actuation system as well as elastomers for the skin material and laboratory equipment to ensure the waterproofness and stability of the final system.

Additionally, our team must refine and develop our skills in fluid mechanics gained from prior coursework in the Mechanical Engineering degree at University of Michigan. Determining the pressure present on the hull's surface is integral, as preventing the dimples from actuating under ambient water pressure as well as from failing to actuate can prevent our entire project's point. This also brings up the point that solid mechanics and potentially finite element analysis skills will be used in our project to determine the precise depth of depression that our elastomer will exhibit and selecting one that fits our needs.

Our selected concept is capable of fulfilling every single objective, depending on how certain upcoming decisions are made. For example, our dimples will be able to form depending on how we select the elastomer that will be used, which will inform how powerful of a vacuum is required and therefore also determine how much power is used. Our concept allows for the room to make different choices but our analysis must show that these different choices satisfy each requirement as well as not impinging on other requirements.

Our project has three main verification processes that must all be fulfilled in order to determine the success of our project. First, is the determination of pressure at the surface of the vessel, this must be able to be withstood by our chosen elastomer. Next, is our solid mechanics analysis of

the deformation of our skin at the dimples, this will inform our elastomer choice. Finally, going together with the previous verification method, is our determination of the internal pressure created by our selected vacuum device. For the solid mechanics and fluid dynamics, FEA and CFD can be performed if necessary, to assure the success of our system. With all these analyses performed, we only need to compare the analytical values with those in our requirements, or perform pass/fail tests as needed, including but not limited to, measuring tests, waterproofness tests, etc.

11.0 Engineering Analysis

11.1 Pressure System Analysis

The primary requirements associated with the pressure system are meeting a -13 PSI system requirement, having two independent sides of operation, ensuring that actuation from external hydrostatic and dynamic pressures are an order of magnitude smaller than what the system actuates too, and ensuring operation is safe.

The maximal pressure change achievable by our pressure system is limited by the lowest rated component of our system. Normally, this is the vacuum pump of the system, however we have deliberately chosen a pump with a very low minimal pressure rating, achieving an ultimate vacuum of 5 Pa above true vacuum (or 0.001 PSI above vacuum, or -14.68 PSI), meaning that our system will be capable of achieving the necessary pressures [26]. We do have an accuracy limitation in the MPRLS pressure sensors we use in our feedback system, where they can no longer hold a ±1.5% pressure reading below 6 KPa of absolute pressure (-13.8 PSI), but is not damaged by these pressures [27]. By our specifications, this is not an issue as we still reach the required pressures and will not incur any damage, but we want to accommodate this issue in the pressure control system to allow the full use of our pump's pressure range. To this end, our control code will include accommodation for this edge case to allow continuous connection to the pump when we wish to operate at the extreme ends of our pressure range.

To allow for independent side actuation from the pressure system perspective, we must ensure that any valves or solenoids used to separate the sides are rated for our pressure operation range. We can plumb the solenoids or values to experience the pressure differential in the same way as a positive pressure system, and therefore may use regular pressure specifications. The selected solenoids are rated to 115 PSI, and are thus adequate [28].

To ensure that the dynamic and hydrostatic pressures incurred during the operation of the device remain within manageable limits, they have to stay at least an order of magnitude below our operating pressure of -14.6 PSI. The hydrostatic pressure is a function of only the submersible's depth, and since this is held constant, we may calculate and account for it in data management. It will have an effect as if we had added that extra pressure to the operating pressure of the device, like having someone push on one side of the skin while we pull from the other with vacuum. The hydrostatic pressure can be estimated by equation RM below, and at a submerged depth of 0.5m,

has a magnitude of 4.9 KPa, or 0.7 PSI. This is small enough to both account for and be well under the threshold for allowable pressure. Even if it were not, this pressure is a constant value which can be accounted for in data processing, and is of limited concern.

$$P_{hydrostatic} = \rho g h \tag{RM}[29]$$

The dynamic pressure, however, will vary with the submersible's tow speeds, and will vary across the length of the device as we generate fluid effects that vary flow velocity. Therefore, it can not be easily accounted for in analysis. We may estimate the average dynamic pressure of an incompressible fluid flow using equation GJ below, however localized effects may vary slightly when flowing over a textured body like ours. In our most demanding planned test, we plan to operate at speeds of 4 m/s, and thus have a dynamic pressure value of 8 KPa, or 1.1 PSI. This also falls within our order of magnitude limit on external pressure and is thus allowable.

$$P_{dynamic} = \frac{1}{2}\rho u^2 \tag{GJ}[29]$$

As for safety of operation, we wish to at all times ensure that the state of the pressurized system is easily discernible and that there is a quick, easy, and safe way to manually depressurize the system in case of an electrical, mechanical, or software failure. We aim to adhere to the guidelines set in ISO 4126, specifically for relief valves and pressure gauges [30]. To this end each side of the device is equipped with a manually operated relief valve, rated for more than 2x the operating pressure. This allows the operator, at any time, to equalize system pressure. The system is also equipped with a glycerin pressure gauge on each side to allow easy reading of each side's absolute pressure, and has a range from absolute vacuum to 2x atmospheric pressure, which exceeds the operating range of the device.

11.2 Skin Analysis

We have two primary concerns with our skin, that it will not fail under operating pressures up to 100 KPa, and that we can deform to a significant enough depth of .01”. To estimate the depth of dimples, we may use the Rayleigh-Ritz method to calculate deformation by energy storage and an assumed shape profile [31]. For simplification of this technically complex problem, we will assume the deformation occurs over a characteristic square area (-a,-a)<(x,y)<(a,a), we will treat the pressure as a uniform load, and assume the dimple can be approximated by a parabolic divot the full size of the same characteristic area. This characteristic area is defined to occupy the same area as our circular dimples on the hull. The code used to derive this formula may be found in appendix B, figure B1-3, but the end result is equation wp below.

$$u_{(0,0)} = \frac{-15a^4 w_0\left(-1+\nu^2\right)}{22Et^3} \tag{wp}$$

The two materials we wish to evaluate their feasibility for skin use are 1/64” neoprene and .010” TPU sheets, with their listed properties and the calculated maximum dimple depth for each shown below in table TZ. There is a degree of uncertainty in the youngs modulus of these materials, as different recipes by different manufactures can lead to relatively wide variations in specifications, however the found values of .13” and .09” are significantly above our required depth, and thus we feel confident that either skin will meet our dimple depth requirement.

Property	**Neoprene**	**TPU**
Pressure (W_0) [Pa]	100*10^3	100*10^3
Characteristic length (a) [m]	2.2*10^-3	2.2*10^-3
Thickness (t) [m]	.00039	.00025
Poisson's ratio (v) [unitless]	0.48	.46
Young's Modulus (E) [Pa]	6.1*10^6	35*10^6
Divot Depth ($u_{(0,0)}$) [m] {in}	.0034 {0.13”}	.0023 {.09”}

Table 10: Properties used to calculate maximum dimple depth of candidate materials and the found depth [32]

In terms of ensuring safety from failure, neoprene has ~280% elongation at break and TPU sits at around ~180% [32]. Using the above actuated pressure at our upper limit of 100 KPa, we can find the deformed length across the deepest parabolic arc of each dimple and then calculate a deformed length % at our maximum value. This is relatively easy as we just find the arclength of the parabolic cross section at y=0 of each found material's dimple geometry. We find neoprene to have a maximum deformed arc of 8.46mm, and therefore an elongation of 92%. For TPU we find it to have 6.66mm arc, and therefore an elongation of 51%. Both of these values are well below the failure elongation values, and therefore both these materials should be under no risk of failure at our operating pressures. For more detail on this calculation, see appendix B, figure B4. Both of these samples, meeting our requirements, will be tested for how well they adhere to a 3D printed surface marine epoxy and for water permeability on a small hull sample. Should both pass these tests, TPU will be selected as it is a slightly cheaper material.

11.3 Electrical and Control System Analysis

We have two requirements primarily dealing with electronics, a power limit and a safety limitation to not introduce current into the water. The power requirement is relatively easy to check. We have one large power draw for the system, the pump, which peaks at ~180 watts. The solenoids operate at ~6.5W each, and an arduino uno typically doesn’t pull more than 2W, which puts us comfortably under our power usage limit of 1000W, even if all systems are maxing out at once.

Electrical water protection is relatively simple because the electronics are all offboarded. All that must be done from a safety standpoint, since the electronics will be stored in a dry area with the onboard MHL computers and monitors, is to make sure they have minor protection from mist or ambient moisture. For this reason electronics will be stored in a plastic container, which is likely needed to transport them without damage anyways. We will still perform our dielectric testing to ensure the system is isolated from the tank, but the only connection point is several feet of plastic, nonconductive, pneumatic tubing, and we are therefore unconcerned, as this should be an easy test to pass for our design.

While we have no requirements about the responsiveness or accuracy of our electronics system, it is still worth considering for the sake of performance. We have two MPRLS pressure sensors, one for each side of the device. These devices operate using static I2C addresses and therefore have to run through a multiplexer to get communication without bus collisions, which increases the clock time of each device by a factor of two. However, this still means we should be collecting data at 50kHz, plenty sufficient for this system. We should also be able to, in theory, operate our solenoids at this speed as well, however we will likely limit their actuation to something closer to 25 Hz to preserve the equipment and ensure the valves have time to fully cycle once powered, as well as to avoiding burning out our relays. This should be plenty sufficient, as our pump is rated for 3.5 ft^3/min of vacuum volume, meaning it takes the pump ~0.8 seconds to evacuate one side of our test device, which has a volume of .046 ft^3, not including tubing. Even though this system is technically second order and therefore doesn't have a uniform time constant, we may estimate the magnitude of the time constant across our operating range by assuming the full time to vacuum is 4 times the time constant, 4τ, and therefore estimate the time constant at roughly 0.2 seconds.

The ratio in the operating frequency of the solenoids and the time required to evacuate the chamber means we should be able to hold our pressure within a deadband with an accuracy of ~1/20 the operating range of the vacuum, meaning a ±0.35 PSI accuracy. This value could be held even tighter if we find we can operate the solenoids at a higher frequency, however we will refrain from testing that until we verify the control schematic as planned is functional. This range is also on a similar scale to the error of our pressure sensors, at 1.5% of measured pressure, meaning ±0.2 PSI at very low pressures. This means that increasing the frequency of the solenoid operation much more would have diminishing returns for accuracy, as the sensor's accuracy would soon become the dominant error source.

11.4 Hull Analysis

There are currently a few requirements that can be related back to the hull of the UUV. The first of those requirements relates to the shape of the UUV as a whole, that being the UUV must have a streamlined body having a diameter to length ratio between 7 and 14. The current hull design has a diameter of 45mm and length of 375mm, this makes the ratio of diameter to length 8.3 which lands comfortably within our requirement. This also relates to another requirement, that

being that there must not be a cross section greater than 1m x 0.5m on the UUV. This requirement exists in order to ensure that the UUV will comfortably fit within the MHL's tow tank.

Another requirement relating to the hull relates to the waterproofing of the interior of the hull. In order to meet this requirement the hull is designed to have no openings that will be exposed to the surrounding water. The only holes found on the hull will be covered by the actuating skin.

11.5 Mounting Analysis

In order to meet the requirements laid out for the recording of data, the UUV must be able to mount to the MHL's tow tank in a way that allows the UUV to move with the carriage and record data for each of the UUV's actuation. The mounting hardware must also be designed in a way that it will have minimal effect on the boundary layer of the UUV.

In order to have minimal effect on the boundary layer, the mount will be designed to emulate an airfoil. This means that the mounting hardware will have a larger leading part of the mount followed by a long, thin tail.

In order to allow for measurable forces resulting from the actuation of the dimples, the mount will include a ball bearing found near the leading edge of the mount which will allow the UUV to rotate freely along the yaw axis. The UUV will then be constrained on the rear with a connection straight to the load cell, which will allow the force to be measured.

12.0 Build and Final Design Description

12.1 Relation of Build to Final Design

Because this project is a "one off" test platform for scientific research, the end build of this project is the final product. There may be future similar prototypes to test similar concepts, and further testing involving this device after our semester ends, but our build is not a prototype of a future project or proof of concept, it is a research device, and not intended to be a marketable product. The final design of this project will be identical to the build simply because it must be in order for it to be useful for data collection. We may have recommendations and lessons learned to guide further research, however this project will produce a built final testing device.

12.2 Pressure System Build Details

The pressure system describes the components of the control system specifically handling pneumatic elements. It consists of the elements shown below in the pictorial diagram of figure 11. It consists of a vacuum pump, meant to evacuate the side of the system of pressure, which is tee-d off to two 12V solenoid valves. These valves serve to pump airline access to each side of the vacuum individually. This solenoid then tee-s off to either the left or right side main pressure line, which will ultimately terminate on the hull of the device. On each main pressure line, we

connect a second solenoid valve to vent to line, a glycerine pressure gauge, an absolute pressure sensor, and a manual pressure relief valve. All components and connections are intended to mate to a ¼” OD push to connect pneumatic tubing, and all screw fittings, aside from the pump, are ¼” NPT, with the pump requiring ⅜” NPT. Additionally, all selected components, including hosing and connectors, are rated within our operating pressure range.

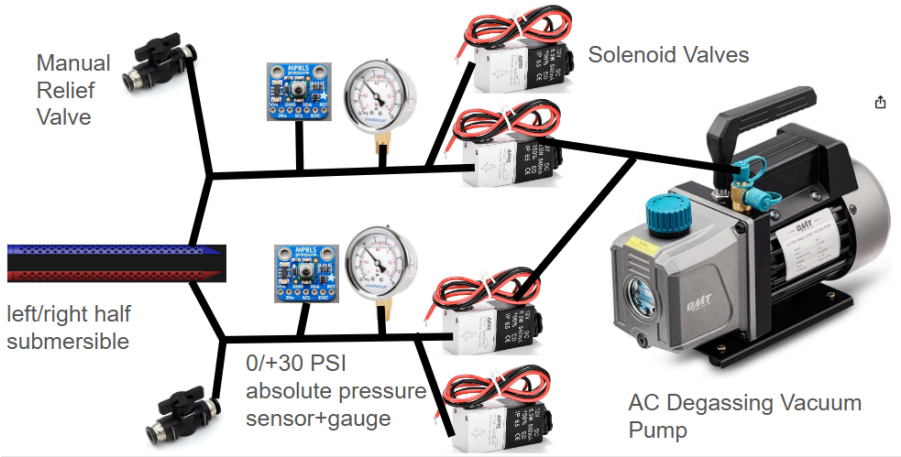


Figure 11. A pictorial diagram showing the components of the pneumatic system and how they are connected together.

Shown below in figure 12 is the schematic for this system. The significant detail of note here is that the solenoid valves are plumbed backwards to how they would normally be in a pressured air system. This is because in a vacuum system, the high pressure side of the system is the actuator, not the pump, and similarly the high pressure side of the system on the vent solenoid is the ambient air.

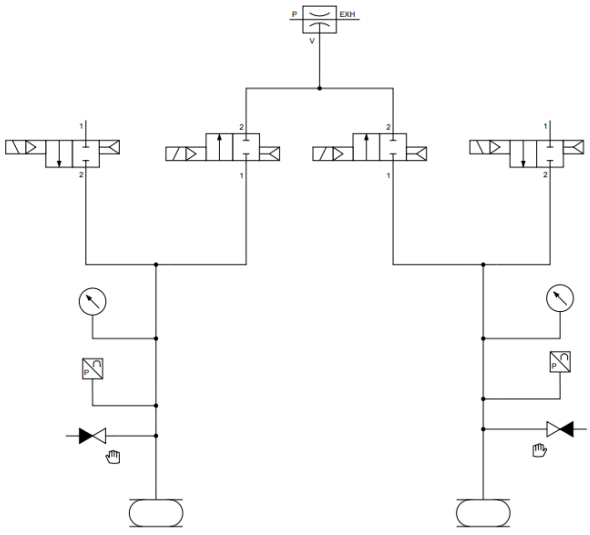


Figure 12: Pneumatic schematic of the pressure system.

Shown below in table TW is the bill of materials for the pressure system. Some components have potential crossover between different systems, and will be included where most appropriate. For example, the pressure sensor will be included in the pressure system, not electronics, and the skin will be included in the hull section, not the pneumatic section. The connector kits below account for all needed pneumatic PTC connector types, and have been selected as it's cheaper to order two kits that have more than what we need than order the individual parts from McMaster-Carr. These components account for $265.85.

Adafruit	MPRLS digital absolute pressure sensor	3965	2	$29.95	$59.90
Amazon	1/4" ptc toggle valve 5 pack	B0D5Y1XWDX	1	$11.99	$11.99
Amazon	-30 to +30 psi gauge	B08ZHXFYKN	2	$9.93	$19.86
Amazon	1/4 HP vacuum pump	B0CSGDHQML	1	$62.99	$62.99
Amazon	1/4" npt to 1/4"npt Fem-Fem coupling 2 pack	B082V8FJQJ	1	$4.99	$4.99
Amazon	PTC connector kit with Tees	B07RSLDDBR	1	$12.99	$12.99
Amazon	2 way/ 2 port 12V solenoid valves	B0FH78JRQ8	4	$12.48	$49.92
Amazon	ptc secondary fittings kit with NPT attachments	B0FH4RZ4GV	1	$16.99	$16.99
Mcmaster	1/4" OD Pneumatic Tubing	5648K31	1	$21.50	$21.50
Mcmaster	3/8" universal to 1/4" ptc	7699N18	1	$4.72	$4.72

Table 11: BOM for pneumatic system

There are no custom manufactured parts in the pneumatic system. The only work to be done is cutting sections of tubing, which can be done with hand clippers or snips. All assembly can be done with hand tools available in the x50 assembly room.

12.3 Electrical System Build Design

The electrical system describes electronic or control components used to actuate the pressure system. Some components will be shown in the electrical system diagrams that are technically part of the pneumatic system, but must be controlled by the electrical system and therefore makes sense to show them for wiring purposes. Shown below in figure 13 is a simplified diagram of the electrical system. This is not a complete wiring diagram, but a simplified diagram showing the components of the system and what they need to connect to. In this diagram, green wires represent signal, red 5v power, blue and purple 12V power, into and out of the relays respectively, and brown represents 120V AC power. The system consists of 4 12V powered, 5V actuated relays used to actuate the solenoid valves, controlled by an arduino uno, with power supplied by a 120V AC to 12V DC wall power adapter. There are also the two MPRLS absolute pressure sensors, which send their data to the arduino though a TCA9548A I2C multiplexer, which is needed to handle the I2C bus since these sensors have static I2C addresses. The final component is the vacuum pump, which plugs directly into 120V AC power.

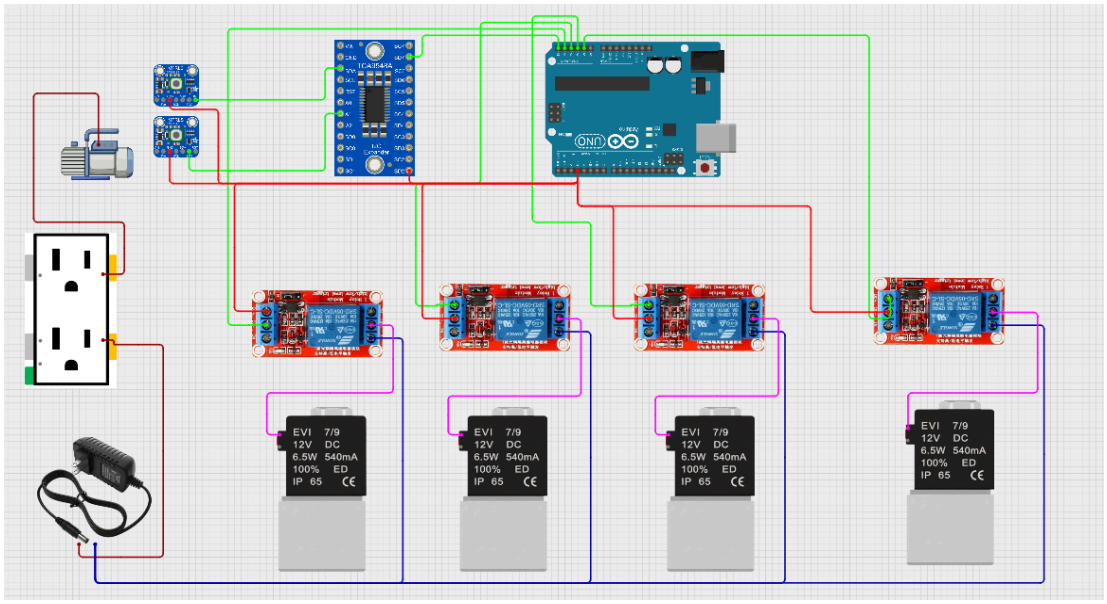


Figure 13. A simplified diagram showing the electrical system and the interactions of components.

Shown below in figure 14 is the full wiring diagram for the electrical system. It is more complex than the above diagram, but also more technically complete and is what will be replicated when the electrical board is created. Both of these diagrams have been created using Cirkit Designer [33].

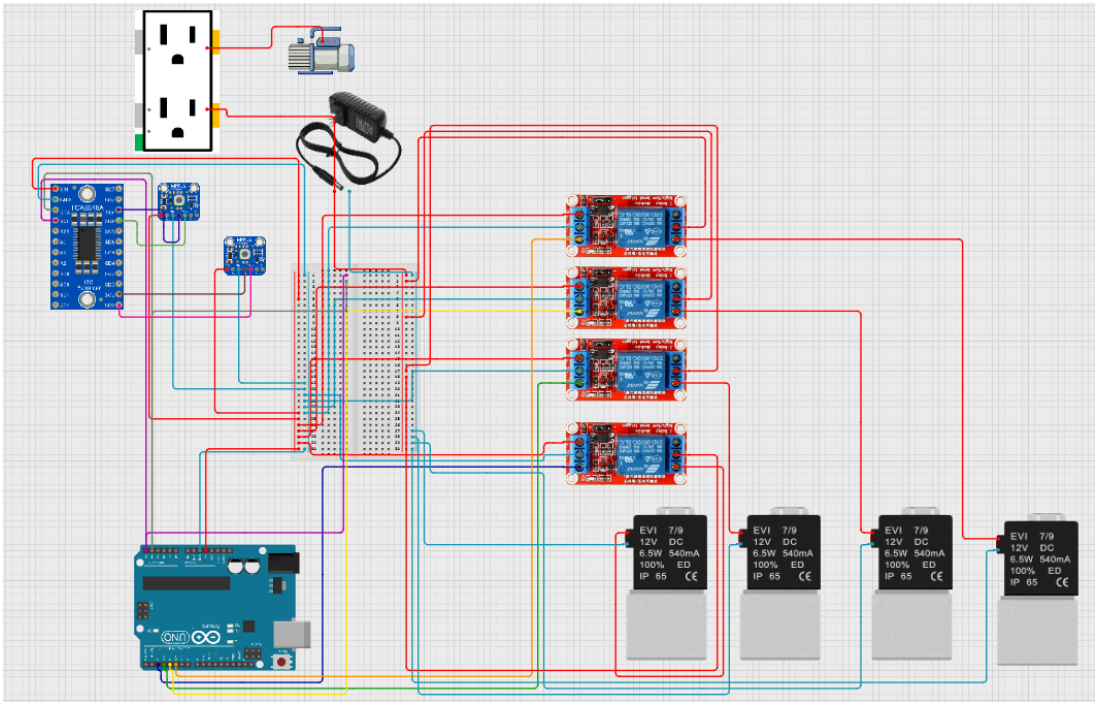


Figure 14. A complete wiring diagram for the electrical system

Shown below in table WM is the BOM for the electrical system. We have not accounted for each wire individually but instead ordered a breadboard kit with jumpers included. The electrical system accounts for $67.03.

Amazon	Arduino uno	B008GRTSV6	1	$27.60	$27.60
Amazon	breadboard and jumper kit	B08Y59P6D1	1	$9.99	$9.99
Amazon	12V power, 5V actuated relay 4 pack	B095YFJ69T	1	$6.99	$6.99
Amazon	120AC to 12V DC wall power converter	B01GD4ZQRS	1	$7.89	$7.89
Amazon	TCA9548A I2C multiplexer	B017C09ETS	1	$14.56	$14.56

Table 12: The BOM for the electrical system

There are no custom manufactured components of the electrical system nor any custom made connectors or cables. The only soldering work needed is to solder the pins onto the multiplexer and the pressure sensors, as well as creating a 12 gauge harness for the solenoids, which can be done in the x50 assembly room, as can all other assembly. No work is required using 120V AC power as all components interfacing with 120V AC power are pre assembled.

12.4 Control System Details

The electrical and pneumatic system will be controlled using an on/off control structure similar to that found in AC/heating systems. The system has 3 useful states: depressurizing, venting, and sealed. Each side may operate independently of each other, and may be experiencing a different state of operation from the other. In depressurization the ambient air solenoid is closed and the pump solenoid is open, allowing the vacuum to remove air from the system. In venting the ambient air solenoid is open and the pump solenoid closed, allowing air to re-enter the system. The final state closes both valves to hold the pressure of the system constant. The idea is to set a deadband region, or hysteresis, around the desired pressure setpoint, and while pressure is below that region, vent, while pressure is in that region, seal, and while pressure is above that region, depressurize. In theory, we should should be able to hold a ±0.35 PSI deadband region while pulsing the solenoids at 25 Hz, as discussed in 11.3, and be able to hold that without disturbance or perturbation of the system via sealing, so long as there are no air leaks leading to gradual pressure rise while sealed.

Code to run this architecture is run through the Arduino IDE in C++, and will utilize Adafruits library for the multiplexer and pressure sensors. The control of the relays will utilize a digital output port on the arduino for each relay that is set to be pulled low to allow for NC action. The logic structure of the code will be custom built to allow tuning of the deadband and frequency limiting of solenoid operation.

12.5 Hull System Details

The hull will be made up of a combination of 3D printed parts. The main part of the hull will be printed in 2 identically mirrored parts. These prints will feature holes for the dimple actuation, as well as the spherical tip, displayed in figure 15.

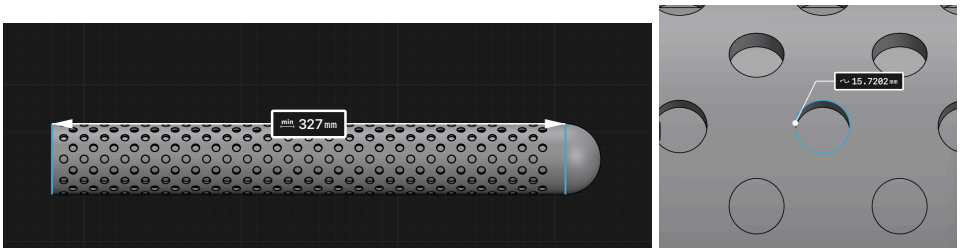


Figure 15. The UUV's hull is 327mm in length, with holes for the dimples measuring at 15.72mm in 3D circumference and 5mm in 2D diameter.

The final piece of the hull will be the rear conical shape. It is designed to fit in the hole that is formed when the 2 halves of the hull are combined together. This piece is shown in figure 16, below.

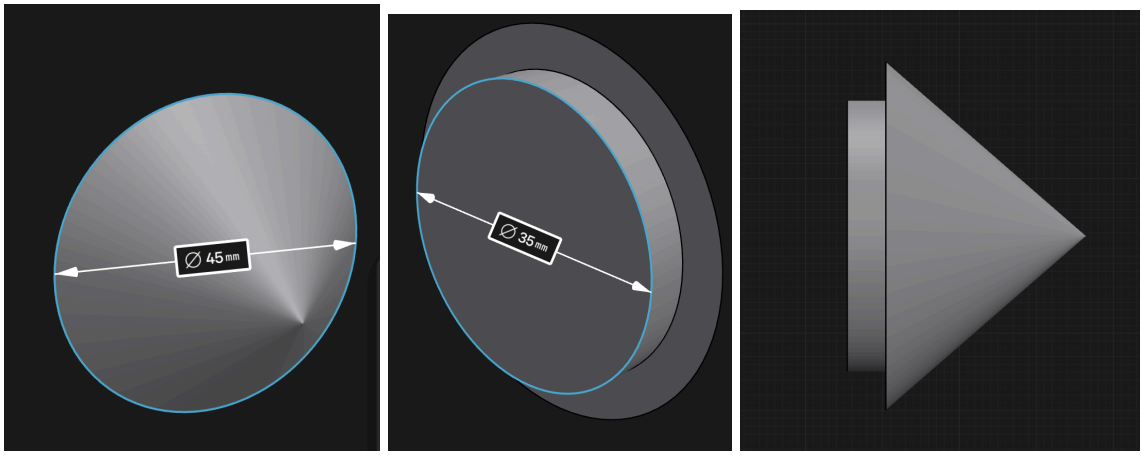


Figure 16. The UUV's rear mounted cone has an outer diameter of 45mm with an extruded cylinder (diameter of 35mm)to attach it to the UUV

These parts need to be able to withstand the force created from being towed across the tank, and they must also be able to withstand exposure to water. So off the bat, we are severely limited on our material selection. This is made even more difficult when considering the material will need to come in the form of filament that can be 3D printed with an FDM printer. To meet these requirements our team has decided to use ABS plastic. Looking at the material properties found on Bambu Lab's website we were able to discern that this filament will meet our requirements.

Mechanical Properties		
Subjects	**Testing Methods**	**Data**
Young's Modulus (X-Y)	ISO 527, GB/T 1040	2200 ± 190 MPa
Young's Modulus (Z)	ISO 527, GB/T 1040	1960 ± 110 MPA
Tensile Strength (X-Y)	ISO 527, GB/T 1040	33 ± 3 MPa
Tensile Strength (Z)	ISO 527, GB/T 1040	28 ± 2 MPa
Breaking Elongation Rate (X-Y)	ISO 527, GB/T 1040	10.5 ± 1.0 %
Breaking Elongation Rate (Z)	ISO 527, GB/T 1040	4.7 ± 0.8 %
Bending Modulus (X-Y)	ISO 178, GB/T 9341	1880 ± 110 MPa
Bending Modulus (Z)	ISO 178, GB/T 9341	1590 ± 100 MPa
Bending Strength (X-Y)	ISO 178, GB/T 9341	62 ± 4 MPa
Bending Strength (Z)	ISO 178, GB/T 9341	39 ± 4 MPa
Impact Strength (X-Y)	ISO 179, GB/T 1043	39.3 ± 3.6 kJ/m²; 21.5 ± 2.2 kJ/m² (notched)
Impact Strength (Z)	ISO 179, GB/T 1043	7.4 ± 1.2 kJ/m²

Table 13. Mechanical properties of ABS plastic.

Skin will be attached to the hull using a thin layer of marine epoxy, and will cover each side of actuation independently. The cost of the hull components, including the skin, is detailed below in Table 14, contributing $56.43 to our budget, making our total expenditures to $389.31. 3D printing is free for us as students at the University of Michigan, and thus is not included in costing.

Mcmaster	1/64" 50A neoprene sheet	1374N31	1	$15.60	$15.60
Mcmaster	.01" rubber sheeting-42" x 2ft long	8611K13	2	$12.00	$24.00
Rev	1.125” OD bearing	REV-21-1916	1	3.25	3.25
Amazon	Marine epoxy 2 pack	B0CT996CM2	1	$13.58	$13.58

Table 14: Purchasing BOM for the hull and attachment subsystems

12.6 Tow Tank Mounting System Details

The mounting system will consist of 2 parts, the foil provided to us by MHL as well as the attachment to hold the UUV to the foil. The latter of which will be 3D printed using ABS, for the same reasons as previously described for the hull. For this report the provided foil will be pictured in green, and the 3D printed attachment will be yellow. As seen in figure 17, the attachment attempts to minimize its interference with the boundary layer of the UUV with its air foil inspired shape. The attachment also smoothly engulfs the sides of the UUV to ensure that there is no sudden change in the boundary layers found between UUV and foil attachment.

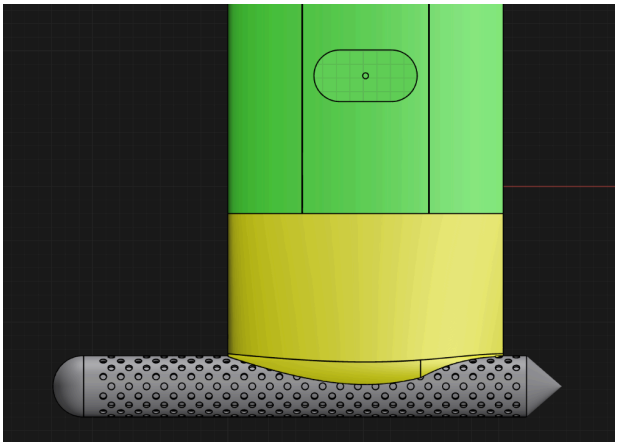


Figure 17. The UUV is attached to a foil provided by MH (green) with a 3D printed attachment to connect them together (yellow).

The foil attachment part will also house the ball bearing and load cell, both of which are critical to the success of our experiments. Within the foil there is a piece of aluminum that we will use to mount our attachment to. This piece will also serve as the mounting point for the load cell. A split view of the mounting foil is shown in figure 18.

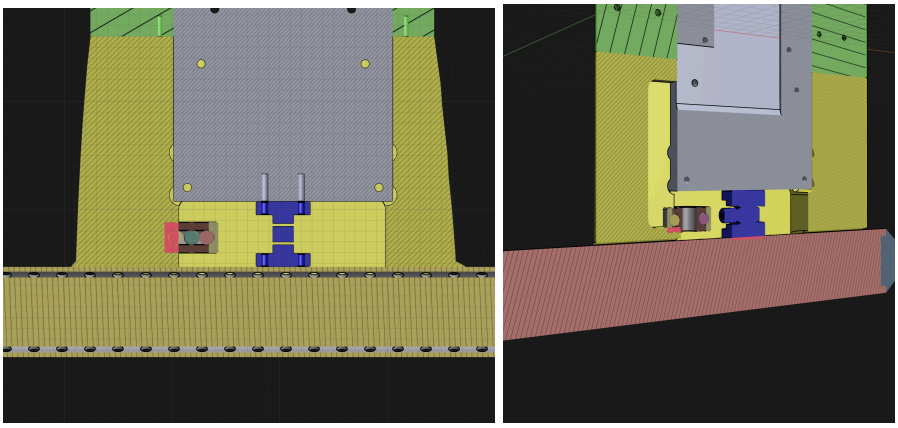


Figure 18. Split view of the assembly showing ball bearing and load cell placed within the 3D printed attachment.

13.0 Description of Verification and Validation Approach.

To verify that the prototype UUV satisfies all critical engineering specifications and stakeholder requirements, a series of experiments and analytical evaluations were developed. These tests intend to confirm the functionality of the pneumatic actuation system, establish quantitative dimple depth control, ensure structural integrity of the hull during the tow tank test, and ultimately use the model to evaluate the hydrodynamic performance of the prototype. These tests are summarized in table X, below. Note that specific requirement codes can be found in the validation and verification traceability log in Appendix C.

Verification Test	Purpose	Requirements Verified	Method	Key Measurements
Submersion & Leak Test	Verify waterproofing and underwater actuation capability	A, E, F	Prototype submerged in aquarium tank while actuating pneumatic system.	Visual leak inspection, pressure stability, successful dimple actuation
Dimple Depth Calibration	Establish a relationship between internal pressure and dimple depth.	A, D	3D scanning of prototype surface at multiple internal pressures	Dimple depth vs. internal pressure curve
Geometric Verification	Confirm prototype geometry approximates typical UUV proportions and meets tow tank size limits	C, G	ED scanning of fabricated prototype and dimensional analysis.	Overall length, diameter, aspect ratio, and maximum cross-section dimensions.
Structural Analysis	Verify hull can withstand hydrodynamic and hydrostatic forces	G	Analytical stress calculations for towing speeds up to 4 m/s	Calculated stresses vs. material strength analysis
Tow Tank Testing	Evaluate hydrodynamic behavior with controlled surface actuation	A, B, G	Towing experiments at speeds from 0.5 to 4 m/s with varying dimple depths.	Hydrodynamic behavior and forces in the yaw direction at ⅛, ¼, ½, ¾, and maximum dimple depth

Table 15: Summary of verification and validation tests to be conducted.

It is important to note that the key stakeholders of this project are engineers looking for quantitative evidence to support a hypothesis. Therefore many of the verification and validation methods overlap. The results from our verification tests will be presented to both Dr. Sareen and the MHL staff, providing measurable evidence that the prototype meets its design requirements.

13.1 Prototype Submersion and Leak Testing

Before any dynamic testing can take place, the prototype must demonstrate that it can operate safely underwater without leakage. A leak in either chamber of the submersible would invalidate test results as internal pressure and dimple depth would not be held constant throughout the duration of each test.

A preliminary submersion test will be conducted using a large, glass aquarium tank provided by the MHL staff. During this test, the fully assembled prototype will be submerged while the pneumatic pressure system is monitored for pressure stability and the skin is observed for visible leaks. Any apparent air bubbles escaping for the device will be treated with marine epoxy before repeating the test. Monitoring the pressure readings will provide clear insight as to whether there are any leaks not apparent to the naked eye.

The actuation system will also be operated while the device is submerged to verify that the pneumatic system can successfully form dimples while the prototype is underwater. Observing successful actuation while submerged can help to confirm that hydrostatic pressure does not interfere with pneumatic actuation and that the skin behaves as intended.

This submersion test directly verifies several of our critical requirements and specifications, including the requirement that the vessel be waterproof and that the actuation system functions effectively while fully submerged. Visual inspection and pressure monitoring will provide both qualitative and quantitative evidence of leaks, and confirm that the actuation system is functional. Although the static aquarium tank doesn't replicate the hydrodynamic conditions of the tow tank, this test will provide reliable preliminary validation that the system is safe and operational prior to tow tank testing.

13.2 Geometric Verification

Our suite of tests is carefully chosen to properly assess validity of the hypothesis that utilizing a dimpling skin on either side of a UUV may generate steering forces.

Without proper Reynold's Number matching between the experimental and operating conditions of a typical UUV, the generation of steering force would not be replicable or scaled for real-world performance. While many engineering experiments can be scaled linearly with size with few scaling effects, fluid dynamics demands the matching of Reynold's Number to ensure that the described fluid dynamics will be observed.

In order to match the Reynold's Number, the size, shape, and speed of the vehicle must stay in line with that of the proposed operating system. Therefore, it is integral that our hull closely matches the design that we generated to be in line with industry standard UUV's.

To ensure the consistency of our prototype to our model, the vessel will undergo thorough inspection including geometric measurement in every critical dimension, that includes the height, width, depth, and measurements associated with the mounting mechanism. This is integral due to the relative inconsistency of 3D printing, so tolerances must be confirmed.

13.3 Structural Analysis

Prior to tow tank testing, the structural integrity of the prototype's hull must be evaluated to ensure that it can withstand both hydrostatic pressure and hydrodynamic loads generated by towing. Since a full-scale withstand test in the tow tank is not feasible within the scope of this project, analytical structural analysis can be used to verify the hull's structural adequacy.

The analysis will evaluate the stresses generated on the hull structure due to the hydrostatic pressure at the system's operating depth and the hydrodynamic forces generated at towing speeds up to 4 m/s. Forces will be estimated using standard fluid dynamics relationships and applied to the hull structure to determine expected stress levels.

These stresses will then be compared to the material strength limits of the 3D printed hull and its structural shape. If the predicted stresses remain well below material failure thresholds, the design will be considered structurally adequate for tow tank testing.

The analytical models will simplify some aspects of real fluid flow, providing a conservative estimate of the loads experienced by the prototype. A conservative estimate of loading is common practice to verify structural integrity prior to physical testing.

13.4 Tow Tank Testing

Hydrodynamic effects are a critical component of this project. However, modeling these effects can be very difficult, as dimples have historically been studied primarily in the context of golf balls, which operate at a different Reynold's Number than a standard UUV. Because of this difference, experimental testing is necessary to evaluate how surface dimpling affects hydrodynamic behavior in operating conditions which are relevant to Dr. Sareen's research.

The primary experimental evaluation will therefore be conducted in the MHL tow tank. During these experiments, the UUV prototype will be towed through the tank at speeds ranging from 0.5 to 4.0 m/s in 0.5 m/s intervals. At each speed, the actuation system will be used to generate different fractions of maximum achievable dimple depth. These depths will include approximately 0, ⅛, ¼, ½, ¾, and maximum. These depths are going to be repeated while either side of the vessel is isolated and again with both sides. An example test matrix is provided in table 16 on the next page.

Test Number	Towing Speed (m/s)	Dimple Depth on Left/Port Side	Dimple Depths on Right/Starboard Side
1	0.5	0	0
2	0.5	$\frac{1}{8}D_{max}$	0
3	0.5	0	$\frac{1}{8}D_{max}$
4	0.5	$\frac{1}{8}D_{max}$	$\frac{1}{8}D_{max}$
5	0.5	$\frac{1}{4}D_{max}$	0
6	0.5	0	$\frac{1}{4}D_{max}$
7	0.5	$\frac{1}{4}D_{max}$	$\frac{1}{4}D_{max}$
8	0.5	$\frac{1}{2}D_{max}$	0
9	0.5	0	$\frac{1}{2}D_{max}$
10	0.5	$\frac{1}{2}D_{max}$	$\frac{1}{2}D_{max}$
11	0.5	$\frac{3}{4}D_{max}$	0
12	0.5	0	$\frac{3}{4}D_{max}$
13	0.5	$\frac{3}{4}D_{max}$	$\frac{3}{4}D_{max}$
14	0.5	D_{max}	0
15	0.5	0	D_{max}
16	0.5	D_{max}	D_{max}

Table 16: Sample testing matrix. This testing matrix will be repeated at 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 m/s for a cumulative 128 tests minimum.

To ensure the structural integrity of the prototype and reliability of the collected data, the first several runs through the tow tank will be treated as preliminary tests. During these runs, our team will closely observe the vessel as it moves through the tow tank, observing from the towing deck, reviewing GoPro footage provided by the MHL staff, and monitoring the collected data for any discrepancies. After these initial runs, we will proceed with the official tests.

Measurements obtained will be from the forces experienced by the load cell on the yaw axis. These forces can then be converted into lift and drag coefficients so that our team can plot lift and drag against Reynolds number, ultimately the plot shapes to determine whether the dimples can create steering force when actuated.

14.0 Feasibility and Performance Demonstration

The feasibility of the smart morphable skin steering system was evaluated through a combination of mechanical validation, analytical modeling, and controlled tow tank experimentation. The primary objective was to verify that the system could produce sufficient surface deformation to alter hydrodynamic forces while maintaining structural integrity.

14.1 Pneumatic Actuation

To validate the actuation mechanism, the effect of internal vacuum pressure on surface deformation was assessed through manual measurement of dimple depths. Dimple depths on the device were recorded under varying pressure conditions, but a precise quantitative relationship between pressure and deformation was not established. Testing consistently showed that increasing vacuum pressure produced deeper dimples, and the system reliably exceeded the minimum depth requirement of 0.01 inches, with a series of 24 measurements with calipers showing an average maximum dimple depth of 0.11±0.01 inches. This confirmed that the pneumatic pressure differentials were sufficient to achieve the necessary geometric changes for the intended boundary layer manipulation. Further, when isolated for the submersible, which has some small leaks, the pressure system is able to achieve near full vacuum, with both glycerin gauges reading approximately -1 bar of gauge pressure (-14.5 psi), and the absolute pressure sensors reading below 60 hPa of absolute pressure. Note that the true value of the reading below this point contains great inaccuracy due to the pressure sensor's increased relative error at low pressure values, but both measurement methods put us well below our stated requirement of -13 PSI of gauge pressure.

Since measurements were taken manually, the results are best interpreted as a qualitative validation rather than a calibrated correlation. To further verify these results, high quality 3D surface scanning could be conducted to create a calibration curve relating chamber pressure to dimple depth.

14.2 Submerge Testing

Structural feasibility was assessed through analytical modeling of the hull and skin system. These calculations show that the 3D-printed hull could withstand hydrostatic loading and towing speeds up to 4 m/s. No catastrophic structural failure or material degradation was observed during testing, including test runs of up to 4 m/s.

We also performed a dielectric leak test on our submersible in the fishtank, in order to verify our system was electrically safe and would not be conducting any electricity into the tank, via a short or otherwise. Our testing involved grounding a multimeter trying to measure voltage, resistance, and current though the water the submersible was in while operating, and between the water and the various power sources of the device. No electrical connections were discovered in any mode, and thus the device was deemed electrically safe. While it was no possible to measure all current draws of the device at once, especially without doing 120V work, we were able to determine from the specifications of our equipment that at no point is it possible to draw more than 200W by operating the device, from all devices combined, thus comfortably staying within the written power maximum of 1kW.

Our team did notice extensive leaking in the early stages of fish tank testing, before tow tank testing. This issue was mitigated through the application of marine-grade epoxy to seal compromised joints and interfaces. While this repair helped to restore the watertight integrity of the model, the added epoxy introduced unintended surface roughness on the model, which is suboptimal for our desired experiment, and we are unable to sand the model for fear of damaging the relatively thin and fragile skin. The epoxy significantly improved the model's leaking issues, albeit there were still small leaks we were unable to find. By installing a coalescing water filter in front of the vacuum pump however, we were able to prevent these small leaks from causing any damage to our system.

This modification may have influenced the hydrodynamic behavior of the system by altering near-surface flow conditions and possibly increasing localized drag. As a result, some of the measured force responses may reflect a combination of intentional surface actuation and unintended roughness effects. Although overall trends in lateral force generation remain valid, this source of uncertainty should be considered when interpreting the model’s performance. Future iterations of the design should prioritize improved sealing techniques during initial fabrication to avoid post-processing modifications that could compromise surface fidelity and experimental accuracy.

14.3 Data Collection and Performance Validation

Performance validation was conducted over the course of our testing sessions at the MHL tow tank. The prototype was mounted to the towing carriage using a custom-designed 3D printed fixture which housed the load cell. The system was tested across a range of towing speeds while independently actuating the port and starboard pressure changers to induce asymmetric surface dimpling. We were able to run a suite of 75 tests over our 3 day window, prioritizing sweeps of data in the 0.5 to 2 m/s range, but including edge case testing up to 4 m/s.

Experimental results showed measurable lateral force generation that varied with towing speed and actuation state. The relationship between towing speed and lateral force is summarized in

figure 19 below, where baseline conditions indicated by 1000 hPa or ambient pressure, and greater degrees of suction represented by decreasing pressure values.

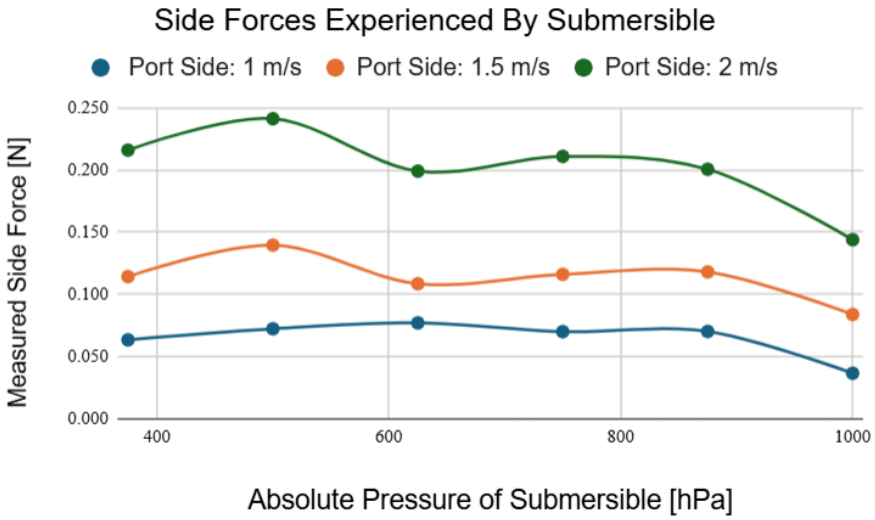


Figure 19: Measured side forces experienced by the submersible at towing speeds of 1 m/s, 1.5m/s, and 2 m/s

When asymmetric vacuum actuation was applied, a consistent jump in lateral force was observed across multiple testing sets. Generally, the magnitude of lateral force increased with towing speed and dimple depth, suggesting that the effectiveness of surface-induced flow modification is more pronounced or more noticeable at higher flow rates. This trend also supports the hypothesis that the morphable skin alters local pressure distribution and can generate directional forces suitable for steering applications. While there is a clear trend in the data, scatter is present at lower towing speeds. This variability is likely due to the added surface roughness from the epoxy mentioned in the previous section.

14.4 Limitations and Considerations

Despite these promising results, there are several limitations that should be considered. Manual measurement of dimple depth introduces significant uncertainty compared to a high-resolution 3D scanning method, and measurement precision is limited by instrumentation and operator consistency. Another point of consideration is that the tow tank only represents steady, controlled flow conditions, not considering the complexity of real-world underwater environments, including turbulence and transient effects.

Overall, the results demonstrate that the smart morphable skin prototype system is feasible within the scope of this project, successfully achieving controlled deformation, maintaining structural integrity, and producing measurable hydrodynamic forces that could translate to steering. Future work should focus on improving measurement precision, developing a more refined assembly, integrating onboard actuation systems, and expanding testing to a greater variety of flow conditions.

15.0 Discussion

15.1 Problem Definition.

Given the rather restrictive time and resource constraints on this project, there are several avenues we would like to have better explored given the opportunity. The first and foremost is a proper exploration of the combined loading experienced by a body such as our. We were limited in our experimental design to the fact that the MHL only had one xyz force load cell available for our use, which extremely limited the ability to collect meaningful data on rotation moments when the prototype experienced combined loadings in multiple directions. If it were a possibility, it would have been ideal to mount the submersible to two different load cells at the front and rear of the device so we could get both force and calculated torque loads, but a singular torque and force capable load cell would also suit our purposes well. If the resources were present, we would have liked to more thoroughly explore the load collecting possibilities available to us.

Given a different set of time and resources, we also would have liked to explore different testing options other than tow tank testing or this device, as it may have been a better experiment for a circulating water chamber. Our time based scope, defined very early in the semester however, led us down this route. A circulating chamber test may have given a better understanding of the hydrodynamic effects occurring as a result of the dimpling due to the more advanced measurement equipment outfitted on the device.

We would have liked to test more materials for the skin as well to find an ideal material for deforming to an adequate depth but not actuating due to lower hydrostatic or dynamic pressures, but our budget was extremely limited and we were only able to purchase two different skin samples for testing. If given the budget, there are 8-12 different materials and thicknesses if we like to have tested and compared to see which would have been ideal.

The last note on our problem definition to make is that we encountered a relatively late semester expansion to our scope, where we wanted to do a laser calibration to associate a pressure within our submersible to a dimple depth using laser scanning equipment. If given more time, this is something we would like to have done, but we were unable to find a lab with equipment of sufficient resolution and availability for such testing on such short notice.

15.2 Design Critique

The most critical flaw in our design was our inability to perfectly watertight the submersible. Of all our issues, this is the root cause of the majority of them. Even under normal conditions, watertighting can be difficult, but especially so when you have a deforming exterior and negative pressure system attempting to draw water in. Even the 3D printed material of the device was porous enough to allow some amount of leak through it. Our solution to this problem was progressively spot checking and applying layers of epoxy or extra skin patches, however issues continued to develop. In future iterations, we would highly recommend a different, less flexible

sealant for the submersible, and manufacturing using a method with a smoother surface finish than FDM printing.

One of the flaws discovered in this design, relevant to the leaking issues, is that the exhaust port of our vacuum pump passed through the oil reservoir. This led to oil foaming and eventual breach of the oil seal if liquid water entered the pump. We were able to borrow an in line coalescing water filter with a tank large enough to deal with our leak volume for a single run, and were able to protect our pump. In future redesigns, it would be better to avoid this issue entirely and find a pump that doesn't have this design flaw.

The other two flaws, also root caused due to the issue of proper sealing, are surface roughness and pressure maintenance. The amount of epoxy applied to the device to try and get a seal lead to an amount of surface roughness that may have started to interfere with the dimpling effect, although we cannot know this for certain, and we couldn't sand it smooth for fear of damaging the skin beneath it. This epoxy may also have been causing some asymmetry in our model, leading to a slightly higher drag and side force on one side.

The inability to properly seal the device also meant that the pressure in the device would gradually increase over time, and require the control system to compensate for that by pulsing the solenoids and introducing a small amount of vacuum. The issue here is that this will overshoot the desired pressure, and the leak will cause the pressure to approach the desired value. This causes a larger degree of error in our pressure value than we planned for. If the seal were perfect, this would not be an issue, and would be less of an issue with a smaller leak. It could be further mitigated with a larger vessel and more control volume in the device, which would dampen the amount of pressure overshooting from the same amount of solenoid pulsing.

Unrelated to our sealing issues, the pressure sensors we have are the only component that is not intended to be used with ¼" ptc connectors or ¼" npt , but are instead a press fit. They needed to essentially be glued on to fit, and while we could achieve a perfect seal here, if the device were to be redesigned, it would be better to purchase a compression fit tubing and then an adapter to get it to connect to the rest of the air system, but this connection was one of the casualties of cost cutting measures to stay within budget.

It would also be nice to have a true pressure regulating system instead of the on-off control system architecture we developed using solenoids. There are available off the shelf solutions with integrated PID controllers for pressure, and devices like these would have enabled a much more precise pressure value to be held even with leaking, however these devices were outside of our budget range. For the pricepoint available to us, our current system performs quite well, however with the solenoids in particular, there is a limit in how frequently you can pulse them open or closed and they tend to heat up quite a bit after prolonged operation. In future designs, if the digital pressure controllers are not an option, we would consider a slightly more responsive solenoid and integrate a heat sink or other cooling measure.

15.3 Risks

As mentioned above, many of the challenges we encountered were related to the sealing of the device. At the root cause level, we attempted to mitigate the leaking as best as we could by spot checking for leaking and applying either epoxy or extra patches of TPU skin to seal the leaks. We were unable to perfectly seal the device, but the leaking issue was significantly improved from the point at which it began by this method. We anticipate this would be an issue, but not to this extent and planned time to attempt to address it, but not to this extent.

After the leak issue became apparent, we identified the risk to the vacuum pump and were able to install a coalescing filter just before the pump to minimize the risk of water entering the oil reservoir. So long as the filter is emptied after each test run, this minimizes the risk of water entering the pump to a minimal degree.

One of the risks we identified early on and gave ourselves time to test was the risk of dimples being actuated as a result of hydrostatic or dynamic pressure. We performed a Rayleigh-Ritz analysis of the anticipated dimple shape with a few potential skin options, and empirically tested two different candidates to select the one that would give us the best dimpling behavior.

We also had identified the risks of operating electronic equipment near a potential water source. Much of this risk was mitigated by storing our electronics in protected areas and running long tubes down to the submersible for vacuum, however we took the additional precaution of placing the electronics in a spare plastic storage container on the small chance a water droplet or small space made its way onto the deck.

The largest risk to the operator of the system is forgetting to empty the reservoir from the coalescing filter. Forgetting to do so may cause damage to the pump and may cause your current run to fail due to pump failure. It is a repairable issue with an oil change, but not desirable. We have mitigated this as much as possible with the addition of the filter, but the risk still remains and it must be monitored.

16.0 Reflection

16.1 Contextual Factors

Using a smart morphable skin for steering has many benefits outlined above, but the main benefit is higher efficiency in UUV’s. Increasing efficiency in UUV’s can decrease fossil fuel usage and benefit local and global health, safety and welfare. UUV’s are used around the world for defense, surveillance, and ocean monitoring, and increasing efficiency can decrease costs, and increase citizen’s safety as well as the safety of the environment. One issue that our design is addressing is the high maintenance costs of traditional fins and rudders. Instead of doing maintenance, in the rare case that the smart morphable skin punctures, operators can simply replace it. This can cause large amounts of waste as old skins are disposed of rather than maintaining them, but considering

the increase in fuel efficiency this cost can be offset. However, the jobs of those who do maintenance on UUV's may be affected. In order to come to these conclusions, stakeholder maps were created with considerations made to each stakeholder's perspective.

16.2 Culture, Privilege, and Identity

Each team member's different backgrounds influenced how we approached the project throughout the semester greatly. Each member had a variety of different expertise, so dividing much of the work was a strong approach. Involving our sponsor, her unique design decisions and foresight into the future of this technology informed our requirements greatly. Throughout the semester she would course correct our design in order to more aptly fit with the future state of the technology.

16.3 Inclusion and Equity

As the designers, we hold the final say in the physical parameters of the design, but our sponsor is the person who provided us with the resources to do the project, so she has a great deal of impact on our design decisions as well. The MHL staff also have an impact since the design will not pass to the testing phase without their sign of approval. Finally, the end-users will decide whether the skin is actually superior to traditional control surfaces or not, so convincing them of the value of the concept is integral to the success of our project. As a team we include diverse perspectives and manage that by placing an emphasis on working alone, and bringing that work to the group for final approval. We decided whose ideas would influence the final design hierarchically, in many cases the project would not be able to go on without passing one person's approval, in which case we value that input highly. Our sponsor is a vastly experienced engineer and especially fluid dynamist so her input was highly concise and relevant, easily being understood for our purposes.

16.4 Ethics

This technology must be evaluated within the context of traditional control surfaces used for UUV control. Optimistically, one could argue that increased fuel efficiency will offset the material used for the replaceable skins. However, it could be argued that with the decreased cost created by this technology, end-users may just end up purchasing more UUV's to offset any gain. This brings up the question of whether or not the benefit of having more UUV's actually adds a sufficient quantity of value to the world as a whole, but at the current state of the technology, this is not possible to know. While questions remain about the potential usage of this technology in defense, potentially furthering the influence of already powerful governments, we have managed these dilemmas by considering the environmental value this technology provides.

17.0 Recommendations

Looking ahead, we have a few recommendations for the project, if it is to continue. The first and most important would be a redesign of the hull/center connection. In the current format we found that the rail connection made it incredibly difficult to ensure both a precise and hard lock into the connector and for the hulls to remain water tight at the same time. If this issue is fixed, then the issue regarding the exhaust valve and oil mixing would be less of a roadblocks as a hull that is watertight will prevent water from entering the vacuum system entirely. This hull redesign would also help make each side of the UAV as symmetrical as possible. Currently, our group had to use copious amounts of epoxy in an attempt to create a water tight hull, but this epoxy does make the system unideal in the sense that the epoxy creates significant roughness in the surface of the UAV, making it asymmetrical.

We recommend the majority of further effort on this should be in producing a smoother, less rough body to test with with less leaking issues. If there can be further experimentation or time available to spend properly sealing and surface finishing the device, you will likely get much cleaner experimental data. We believe that the control system, including the pneumatics, electronics, and code, is largely plug and play with devices of a similar nature, and can be adapted easily to a new device.

We also recommend that some future experimentation take place in a recirculating water chamber. We noticed a few interesting trends in our data, including peaks of side force at certain vacuum pressures, which warrant further investigation that the MHL is not necessarily equipped for. The recirculating water chamber would allow a better study of the vortex and boundary layer behavior of the fluid as it passes over the device, and may offer some insight into the mechanisms causing these phenomena.

We also recommend performing a laser calibration of dimple depth to be able to generate a trend between different commanded pressures and dimples depths, as this is useful in this particular type of study and is needed for publication. We planned to do this ourselves, but unfortunately could not find a suitable time in the semester to schedule these calibrations with the equipment of necessary resolution being booked

18.0 Conclusions

Our work successfully established proof-of-concept for a finless unmanned underwater vehicle that utilizes a smart morphable skin to generate control forces. By mimicking the aerodynamic properties of golf balls, our team designed and manufactured a cylindrical prototype capable of active surface modification to influence hydrodynamic flow. This approach directly addresses the limitations of traditional rudder systems which often increase vehicle drag and are susceptible to mechanical damage in marine environments.

Through the application of the ME 450 iterative design framework, our team was able to successfully develop a model which included a dual-chamber internal skeleton, an offboarded pneumatic actuation system, and a modular mounting interface for tow tank testing. The successful collection of force data at the Marine Hydrodynamics Laboratory validates that asymmetric dimpling could be a viable mechanism for producing measurable steering forces and should be explored further. Further optimization of skin materials and dimple geometry would be required for field-ready applications, but this work provides a foundational technical framework for the next generation of more efficient and durable underwater vehicles..

19.0 Acknowledgements

This endeavor would not be possible without the gracious support and guidance of Dr. Anchal Sareen who sponsored and conceptualized the project. We would also like to express our gratitude to the MHL staff, including Jason Bundoff and Jim Smith, for lending their facilities, guidance, and expertise to us throughout our project. We would also like to share our gratitude with Dr. Shorya Awtar who guided us through the project from start to finish.

Many thanks to our fellow classmates who supported us with our presentations and process. Finally, many thanks to the rest of the ME450 team, including Arthur Hyde, Shanna Daly, Steven Skerlos, and all the student leaders who provided us with invaluable feedback.

References

[1] “What is an AUV?,” NOAA Ocean Exploration, https://oceanexplorer.noaa.gov/ocean-fact/auv/ (accessed Jan. 29, 2026).

[2]MarketsandMarkets, “Unmanned Underwater Vehicles Market worth $8.72 billion by 2030 - Exclusive

[3] S. Prabhu, “How Golf Ball Dimples Affect Its Flight & Aerodynamics,” *SimScale*, Jul. 19, 2016. https://www.simscale.com/blog/how-dimples-affect-golf-ball/

[4] “Effect of dimples on golf ball | download scientific diagram,” Research Gate, https://www.researchgate.net/figure/Effect-of-dimples-on-golf-ball_fig1_312219667 (accessed Jan. 28, 2026).

[5] R. Vilumbrales-Garcia, P. B. Sudarsana, and A. Sareen, "Adaptive drag reduction of a sphere using smart morphable skin," Flow, vol. 5, art. no. E17, 2025, doi: 10.1017/flo.2025.7.

[6] P. B. Sudarsana, R. Vilumbrales-Garcia, and A. Sareen, “On the lift generation over a sphere using asymmetric roughness,” *Physics of Fluids*, vol. 36, no. 12, Dec. 2024. doi:10.1063/5.0241948

[7] “Nimble dimples: Agile underwater vehicles inspired by golf balls | University of Michigan News,” University of Michigan,

[8] J. Katz and PhD, “An Introduction to Automobile Aerodynamics,” *Mechanix Illustrated*, Mar. 04, 2017. https://mechanixillustrated.technicacuriosa.com/2017/03/04/an-introduction-to-automobile-aerodynamics/

[9] “Vision AVTR: Future vehicles,” Mercedes, https://www.mercedes-benz.ca/en/future-vehicles/vision-avtr (accessed Jan. 28, 2026).

[10] Y. Wang, C. Sicot, J. Borée, and M. Grandemange, “Experimental study of wheel-vehicle aerodynamic interactions,” *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 198, p. 104062, Mar. 2020, doi: https://doi.org/10.1016/j.jweia.2019.104062.

[11] V. Radu, “Thanks, Golf Ball! Bugatti’s Monstrous Bolide Has World-First Active Roof Scoop,” *autoevolution*, Dec. 11, 2020. https://www.autoevolution.com/news/bugattis-monstrous-bolide-features-the-worlds-first-active-roof-scoop-152925.html

[12] C. McKenzie, *Quotable Scots*. Mainstream Publishing Company Limited, 1995.

[13] A. Sareen, “First Sponsor Interview,” Jan. 16, 2026

[14] A. Sareen, “Second Sponsor Interview,” Jan. 23, 2026

[15] J. Bundoff and J. Smith, “Marine Hydrodynamics Lab Interview,” Jan. 26, 2026

[16] J. Venetos, “How many dimples are on a golf ball and how they impact flight,” Jim Venetos Golf Academy, https://jimvenetosgolfacademy.com/how-many-dimples-are-on-a-golf-ball-and-how-they-impact-flight/ (accessed Jan. 26, 2026).

[17] X. Ling, Z. Q. Leong, and J. Duffy, “Effects of length-to-diameter ratio on a near Free Surface Underwater Vehicle,” *Applied Ocean Research*, vol. 138, p. 103657, Sep. 2023. doi:10.1016/j.apor.2023.103657

[18] “Pressure-to-depth and depth-to-pressure calculator,” Blue Robotics, https://bluerobotics.com/learn/pressure-depth-calculator/ (accessed Jan. 26, 2026). https://news.umich.edu/nimble-dimples-agile-underwater-vehicles-inspired-by-golf-balls/ (accessed Jan. 27, 2026).

[19] Xylem Inc., EcoMapper Nano: Compact, Autonomous Underwater Survey Vehicle – Specifications Sheet, 2026. [Online]. https://www.ysi.com (accessed Feb. 24, 2026)

[20] B. Axelsen, D. Corrada, T. Leasca, and S. Ramesh, *Analysis of Flow over a Dimpled Airfoil*.

[21] Adam Amran, “Decision matrix,” Tools for better thinking, https://untools.co/decision-matrix/ (accessed Feb. 20, 2026).

[22] M. Alijani, M. Zeinali, and N. M. Nouri, “Designing of the body shape of an autonomous underwater vehicle using the design of Experiments Method,” *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 233, no. 18, pp. 6307–6325, Dec. 2018. doi:10.1177/0954406218820884

[23] N. E. Dowling, S. L. Kampe, and M. V. Kral, *Mechanical Behavior of Materials: Engineering Methods for Deformation, Fracture, and Fatigue*. Harlow: Pearson Education Limited, 2020.

[24] J. G. Leishman, “Bluff body flows,” Introduction to Aerospace Flight Vehicles, https://eaglepubs.erau.edu/introductiontoaerospaceflightvehicles/chapter/bluff-body-flows/ (accessed Feb. 20, 2026).

[25] “Industrial Quick Search,” Advantages, Types Of, Uses, https://www.iqsdirectory.com/articles/hydraulics/difference-between-hydraulics-and-pneumatics.html (accessed Feb. 20, 2026).

[26] “AC vacuum pump,3.5CFM 1/4HP AC Vacuum Pump Kit - Orion Motor Tech,” OrionMotorTech, https://orionmotortech.com/products/3-5cfm-ac-vacuum-pump-kit-vph-a00a-lb?srsltid=AfmBOooQhMKZZ719kqGFaPTNy5iOq3Kc56PBqh1eQvTM3UJb4kuf9eKA (accessed Mar. 17, 2026).

[27] “Micropressure MPR Series Board mount pressure sensor,” Honeywell, https://automation.honeywell.com/us/en/products/sensing-solutions/sensors/pressure-sensors/board-mount-pressure-amplified/micropressure-mpr-series-board-mount-pressure-sensor (accessed Mar. 17, 2026).

[28] “Beduan 2 way normally closed DC 12V Electric,” Beduan 2 Way Normally Closed DC 12V Electric - Beduan Official, https://mybeduan.com/beduan-2-way-normally-closed-dc-12v-electric.html (accessed Mar. 17, 2026).

[29] P. M. Gerhart *et al.*, *Fundamentals of Fluid Mechanics*. Hoboken, N.J: Wiley, 2016.

[30] “ISO - 4126: Safety devices for protection against excessive pressure,” International Organization for Standardization

[31] J. R. Barber, *Intermediate Mechanics of Materials*. Dordrecht: Springer, 2011.

[32] “Online materials information resource - matweb,” Matweb, https://www.matweb.com/ (accessed Mar. 18, 2026).

[33] “Cirkit designer Ide,” Cirkit Designer IDE, https://app.cirkitdesigner.com/ (accessed Mar. 19, 2026).

Appendix A: Concept Generation

A.1 Individual Preliminary Concept Generation

Joel Bhattarai

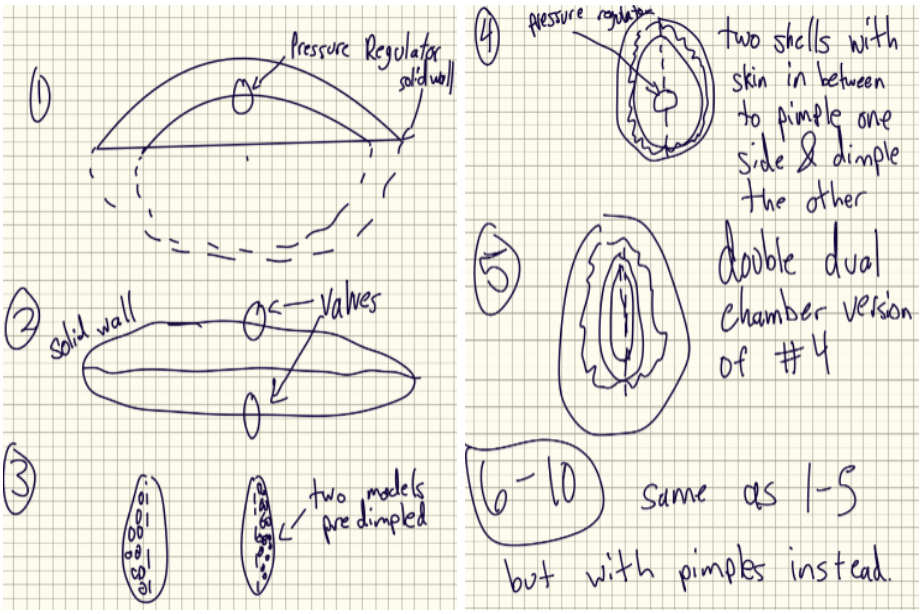


Figure A1. Independent preliminary concepts generated by Joel Bhattarai

Ian Carter

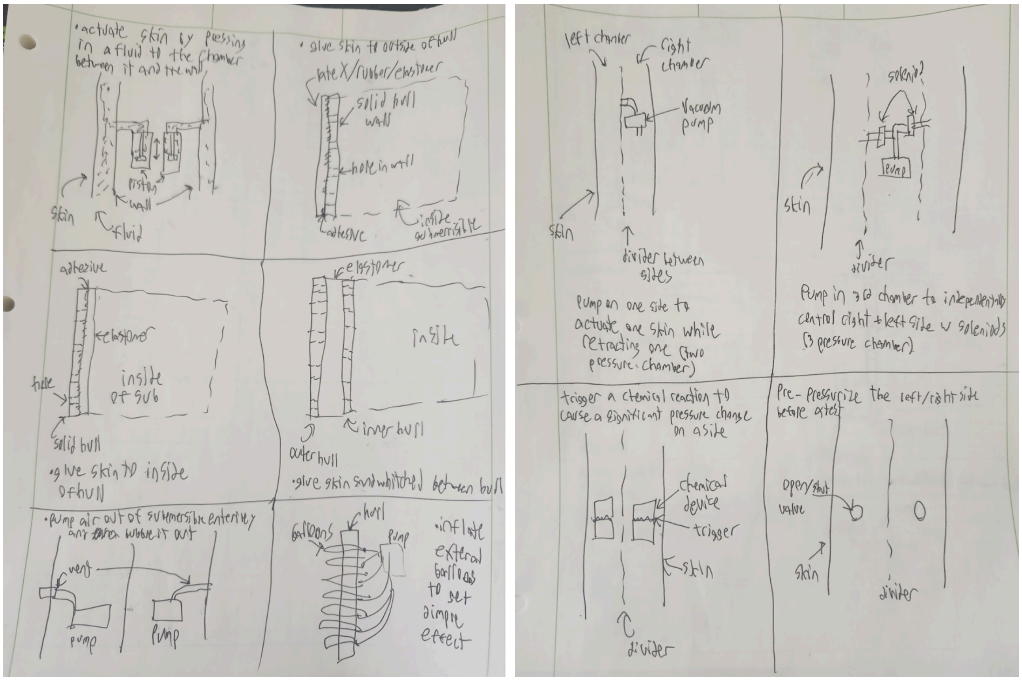


Figure A2. Independent preliminary concepts generated by Ian Carter

Ryan McGlynn

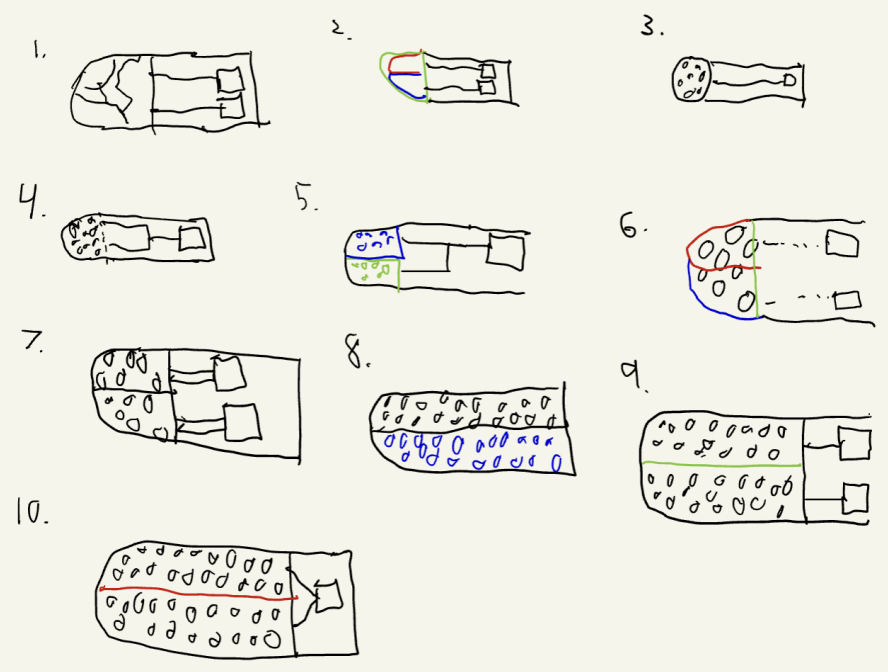


Figure A3. Independent preliminary concepts generated by Ryan McGlynn

Alexa Remirez-Greenwood

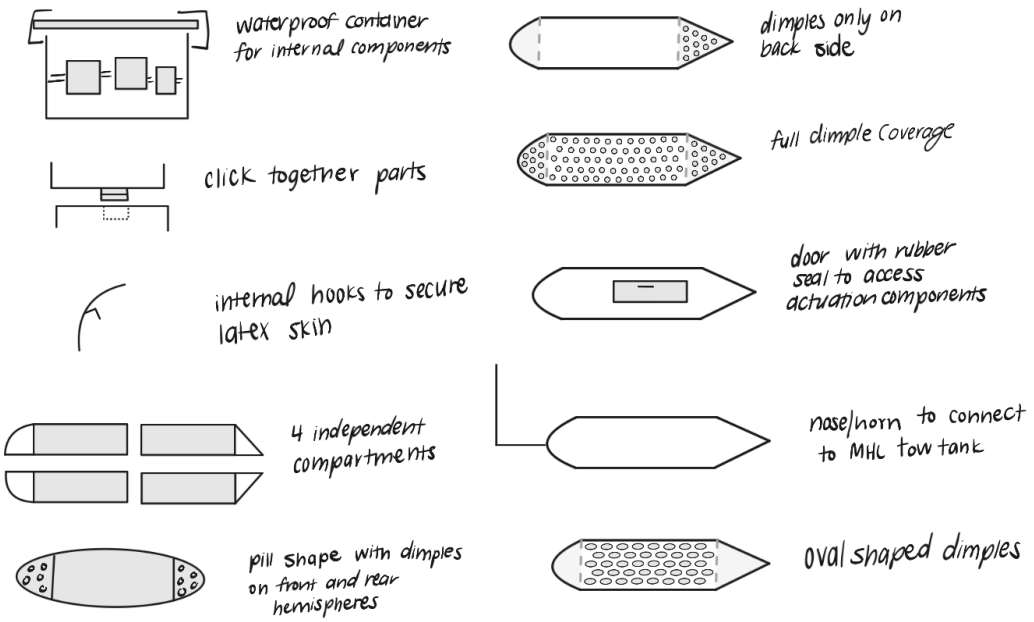


Figure A4. Independent preliminary concepts generated by Alexa Remirez-Greenwood

A.2 Individual Concept Generation Iteration

Joel Bhattarai

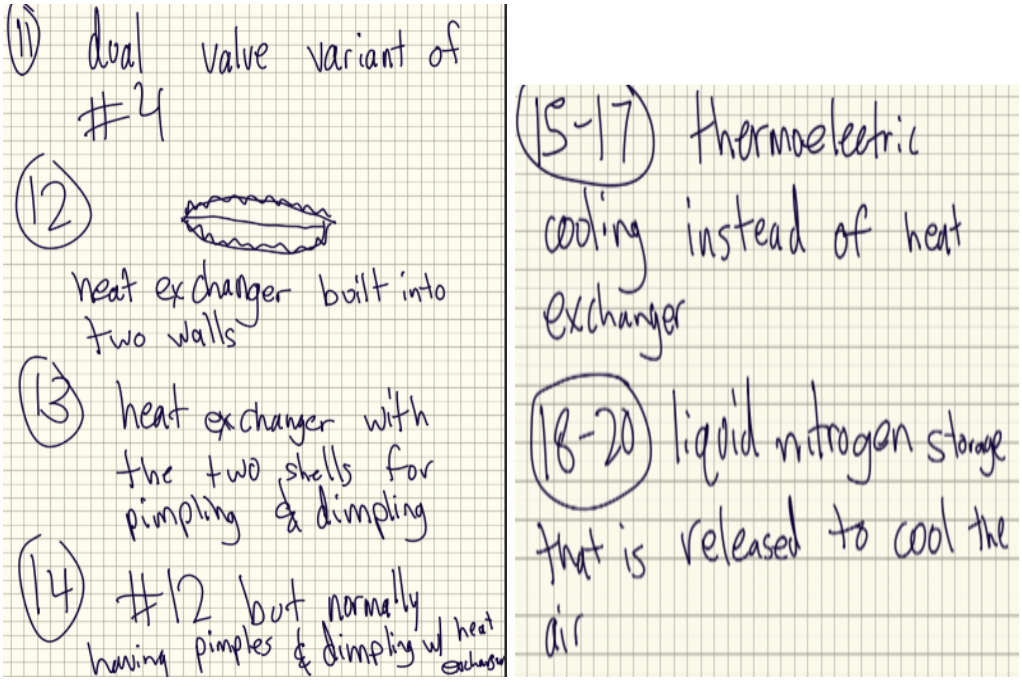


Figure A5. Independent concepts generated by Joel Bhattarai

Ian Carter

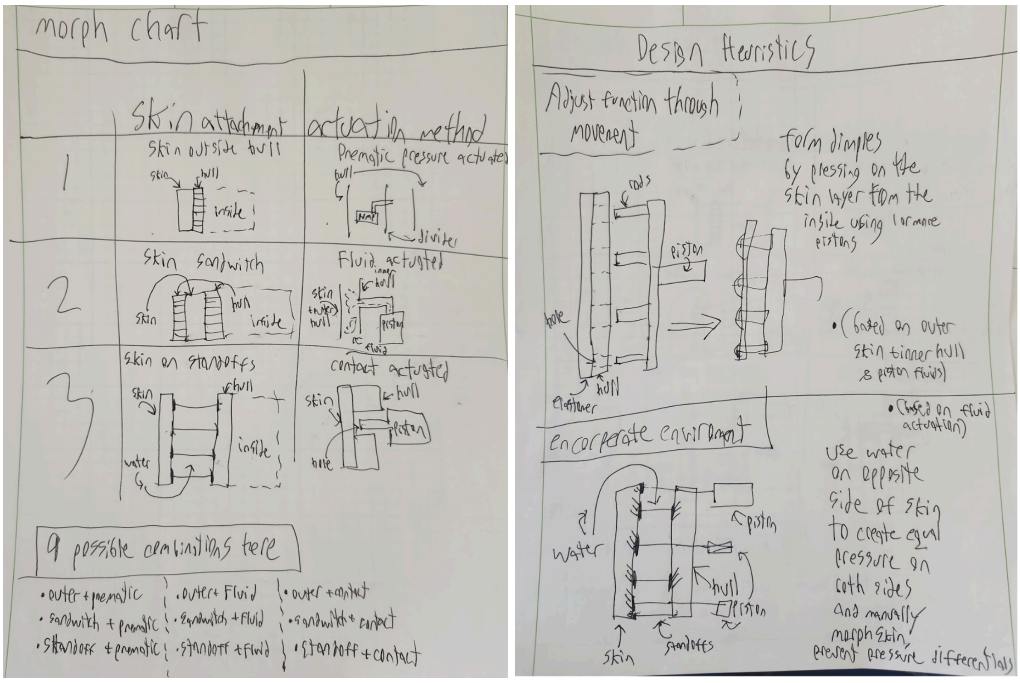


Figure A6. Independent concepts generated by Ian Carter

Ryan McGlynn

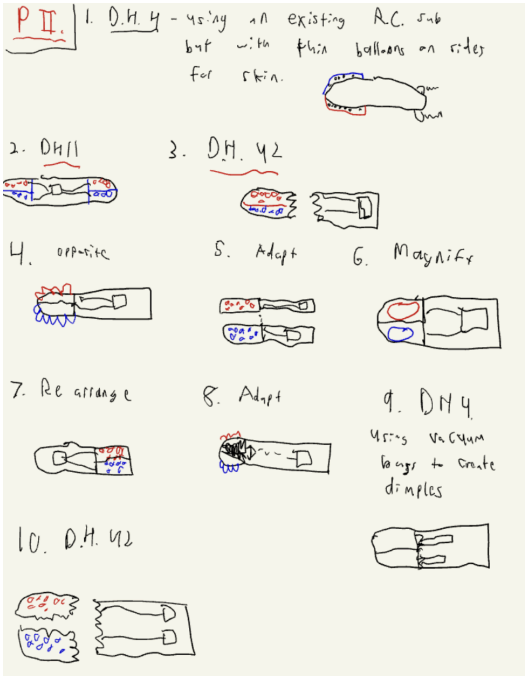


Figure A7. Independent concepts generated by Ryan McGlynn

Alexa Remirez-Greenwood

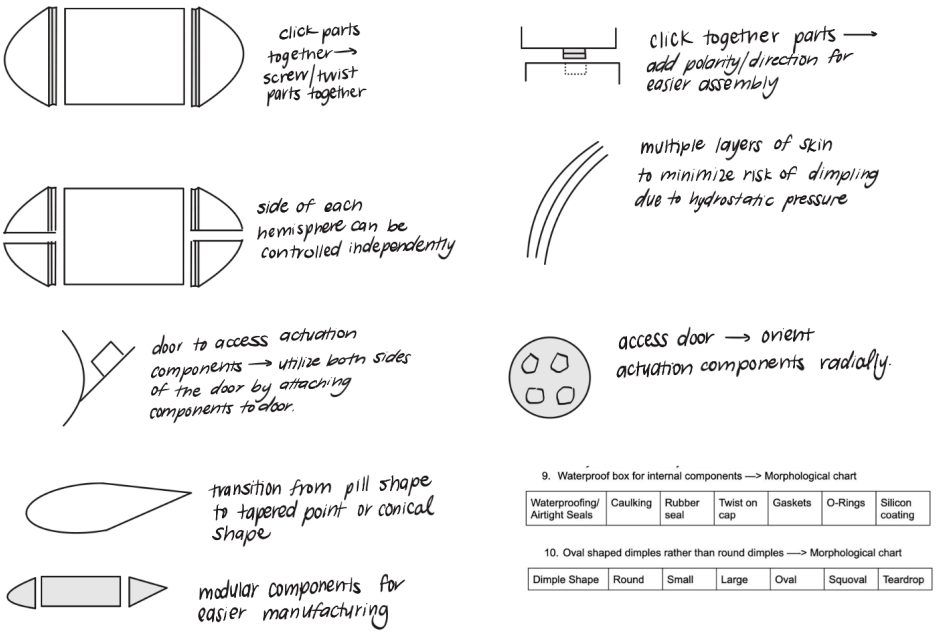


Figure A8. Independent concepts generated by Alexa Remirez-Greenwood

A.3 Team Mind-Mapping

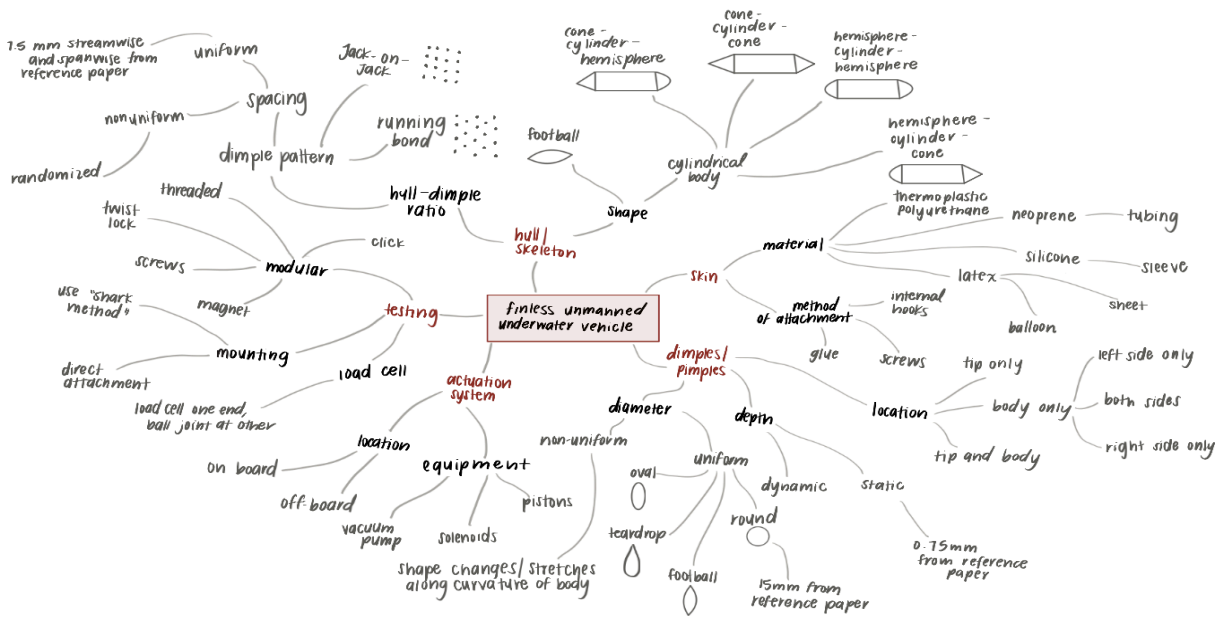


Figure A9. Mind map generated during team brainstorming session.

A.4 Preliminary Morphological Chart Development

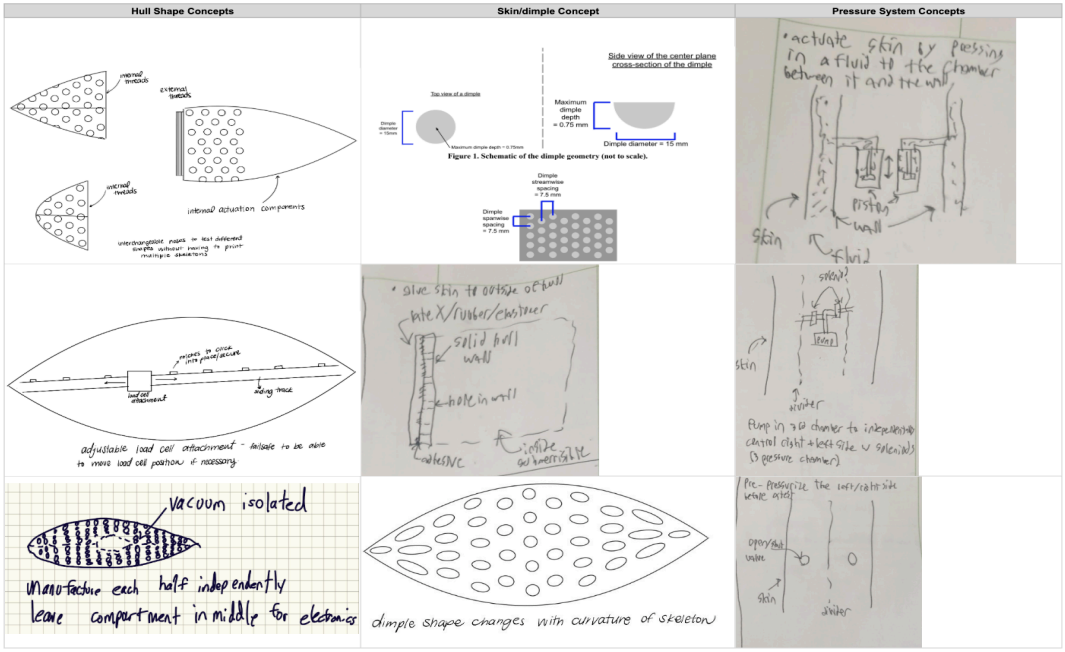


Figure A10a. Part 1 of the preliminary group morphological chart. Note that the morphological chart was determined unsuccessful as ideas were not mutually exclusive.

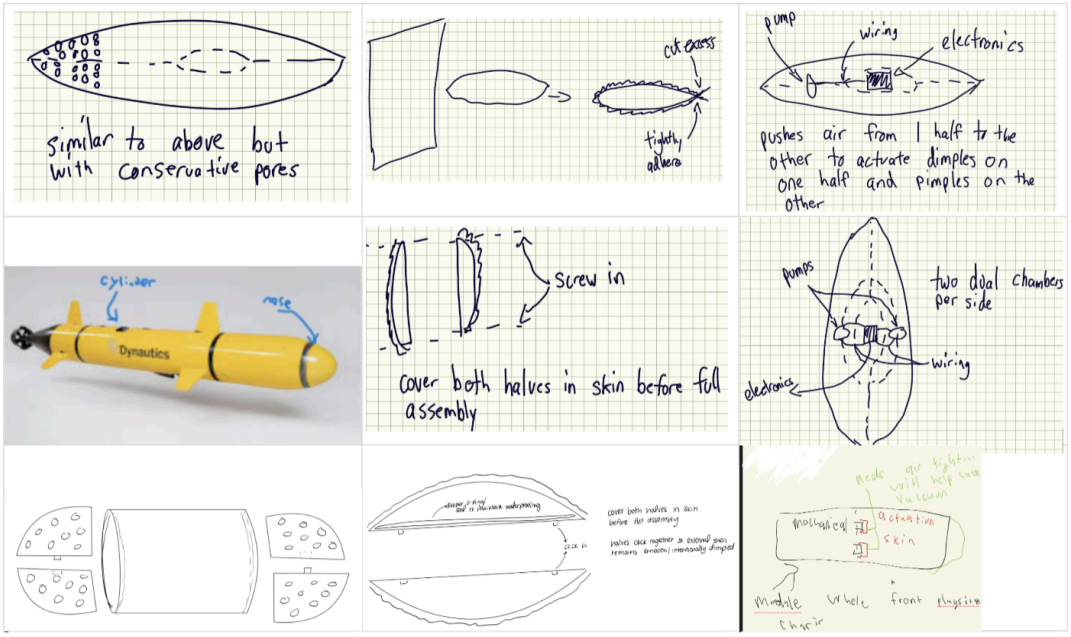


Figure A10b. Part 2 of the preliminary group morphological chart. Note that the morphological chart was determined unsuccessful as ideas were not mutually exclusive.

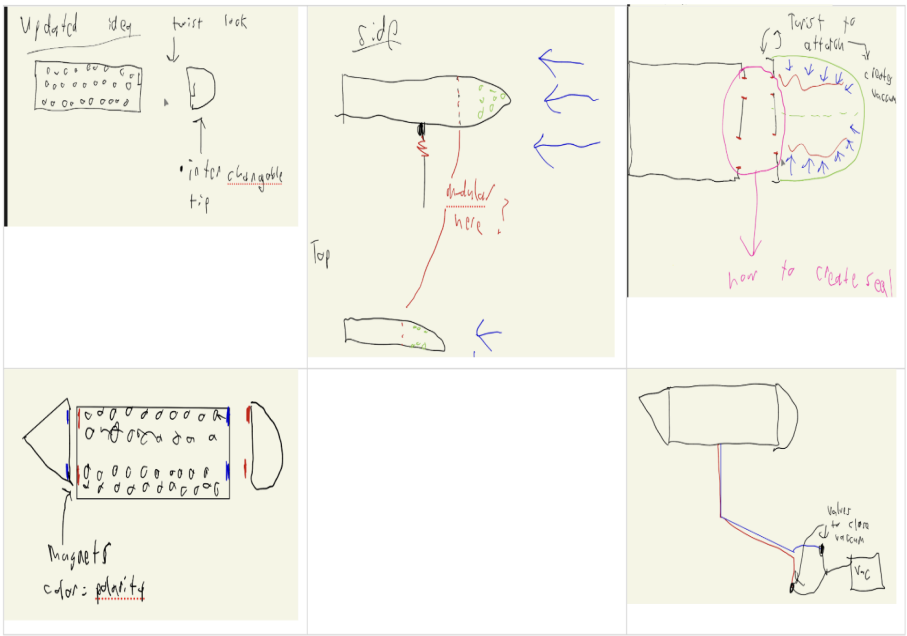


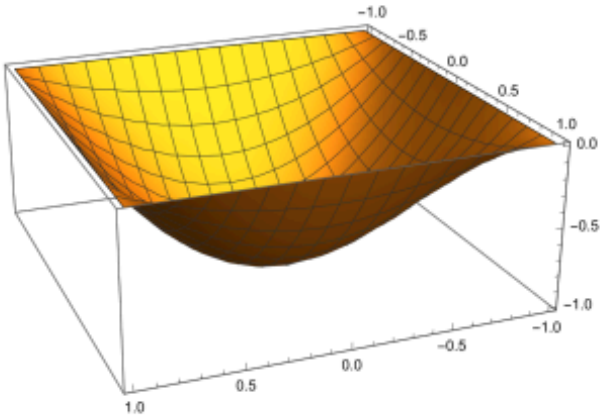
Figure A10c. Part 3 of the preliminary group morphological chart. Note that the morphological chart was determined unsuccessful as ideas were not mutually exclusive.

Appendix B: Dimple Depth and Failure Calculations

The Rayleigh-Ritz method uses a parameterized guess function for a deformed shape and finds the equilibrium point between stored energy in the material and work done by a load to find the degree of deformation. It is intended as an estimation tool to land you in approximately 30% of your desired solution, and is not meant to be 100% accurate. It is however, parameterized in such a way that it's very easy to check various materials of different properties and thickness for their deformation, unlike FEA which would require rerunning a simulation for every material. This estimate uses a square outer perimeter guess function to maintain appropriate boundary conditions, which are much more complex to get in a 4th degree guess function in polar coordinates. While it is not the best possible guess function, the dominant area of energy storage occurs at the center, so the effect on the model is less than using improper boundary conditions would be.

In[1]:=
```
Plot3D[-1 * (1 - x^2) * (1 - y^2), {x, -1, 1}, {y, -1, 1}]
```

Out[1]=



In[2]:=
```
d = e * t^3 / (12 * (1 - v^2))
```

Out[2]=
$$\frac{e\,t^3}{12 \times (1 - v^2)}$$

In[3]:=
```
u = c (a^2 - x^2) (a^2 - y^2)
```

Out[3]=
$$c\,(a^2 - x^2)\,(a^2 - y^2)$$

In[4]:=
```
UperunitArea = d / 2 * (D[D[u, x], x]^2 + 2 v * D[D[u, x], x] * D[D[u, y], y] + D[D[u, y], y]^2) +
  d (1 - v) * D[D[u, x], y]^2
```

Out[4]=
$$\frac{4\,c^2\,e\,t^3\,(1 - v)\,x^2\,y^2}{3 \times (1 - v^2)} + \frac{e\,t^3\left(4\,c^2\,(a^2 - x^2)^2 + 8\,c^2\,v\,(a^2 - x^2)\,(a^2 - y^2) + 4\,c^2\,(a^2 - y^2)^2\right)}{24 \times (1 - v^2)}$$

In[5]:=
```
Usheet = Integrate[Integrate[UperunitArea, {x, -a, a}], {y, -a, a}]
```

Out[5]=
$$-\frac{176\,a^6\,c^2\,e\,t^3}{135 \times (-1 + v^2)}$$

In[55]:=
```
Clear[c]
Utot = Usheet - c * (a^4) * F
```

Out[56]=
$$-a^4\,c\,F - \frac{176\,a^6\,c^2\,e\,t^3}{135 \times (-1 + v^2)}$$

In[58]:=
```
Solve[D[Utot, c] == 0, c]
```

Out[58]=
$$\left\{\left\{c \to -\frac{135\,F\,(-1 + v^2)}{352\,a^2\,e\,t^3}\right\}\right\}$$

Figure B1: The first page of code developed to determine maximal dimple depth, formulated using a point load

In[60]:= $$\text{Disp1} = -\frac{135\,F\left(-1+v^2\right)}{352\,a^2\,e\,t^3} * a\text{^}4$$

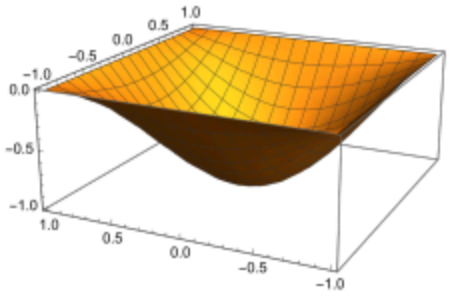
Out[60]= $$-\frac{135\,a^2\,F\left(-1+v^2\right)}{352\,e\,t^3}$$

In[78]:=
```
a = 1;
F = 1 * 10^3;
v = 0.33;
e = 7.17 * 10^10;
t = 0.00635;
Disp1
Clear[a, F, v, e, t];
```

Out[83]= 0.0186156

In[•]:=
```
Plot3D[-1 (Cos[x / 2 Pi]) (Cos[y / 2 Pi]), {x, -1, 1}, {y, -1, 1}]
```

Out[•]=



In[41]:=
```
Suggestion = C * (Cos[a * x / 2 / Pi]) (Cos[a * y / 2 / Pi])
```

Out[41]= $$C\,\text{Cos}\left[\frac{a\,x}{2\,\pi}\right]\,\text{Cos}\left[\frac{a\,y}{2\,\pi}\right]$$

In[68]:=
```
Uforce = Integrate[Integrate[-w0 * c (a^2 - x^2) (a^2 - y^2), {x, -a, a}], {y, -a, a}]
```

Out[68]= $$-\frac{16}{9}\,a^6\,c\,w0$$

Figure B2: Verification that the code above behaves as expected, and beginning of integrating distributed loading

In[95]:= `Solve[D[Uforce + Usheet, c] == 0, c]`

Out[95]= $\left\{\left\{c \to -\frac{15 \times \left(-1+v^2\right) w0}{22\, e\, t^3}\right\}\right\}$

In[70]:= `Disp2 = -(15 × (-1 + v^2) w0)/(22 e t^3) * a^4`

Out[70]= $-\frac{15\, a^4 \left(-1+v^2\right) w0}{22\, e\, t^3}$

Figure B3: Last steps of integrating distributed loading into the solution

```
Clear[a, c, u]
a = 2.2 * 10^-3
u[x_] = c * a^2 * (a^2 - x^2)
h = .0034 (*Value of max depth*)
c = First[SolveValues[u[0] == h, c]]
Integrate[Sqrt[1 + (u'[x])^2], {x, -a, a}]
```

Out[109]= `0.0022`

Out[110]= $4.84 \times 10^{-6}\, c \left(4.84 \times 10^{-6} - x^2\right)$

Out[111]= `0.0034`

Out[112]= 1.4514×10^8

Out[113]= `0.00846152`

Figure B4: Calculated maximum deformed arc length of a cross section of the dimple

Appendix C: Validation and Verification

Requirement ID	Requirement	Specification ID	Specification Description (Include measurable specification, unit, and pass/fail threshold)	Priority	Verification ID	Verification method	Verification testing owner
A	The device must be able to form pimples or dimples on it's skin while underwater	A-001	The controlled device must be able to form concave protrusions of a depth at least .01"	Critical	A-V-001	Empirical testing in small tank at MHL	Team member(s): Ian, Alexa
B	The device must be able to test whether aquatic steering is possible with this technology	B-001	The controlled device must have at least 2 independent sides of actuation (port/starboard)	Critical	B-V-001	Empirical testing in small tank at MHL with visual inspection	Team member(s): Ryan
C	The device must roughly mimic the shape of an average unmanned underwater vehicle	C-001	The main body of the controlled device have a primarily streamlined body with a length/diameter aspect ratio between 7 and 14	High	C-V-001	Visual Inspection	Team member(s): Ryan
D	Dimples/pimples shouldn't actuate just because of local pressure differences	D-001	The device must operate using gauge pressures at least an order of magnitude different (10x) than those at test depth & dynamic pressure: [A positive pressure system must achieve at least 49 Psi and a negative pressure system at least -13 Psi]	Critical	D-V-001	Empirical testing in small tank at MHL with visual inspection	Team member(s): Alexa
E	Skin must not puncture as a result of normal operation	E-001	Skin must be able to withstand 100 kpa of relative pressure without puncture	High	E-V-001	Submerge test in small tank at MHL and visual inspection	Team member(s): Joel
		F-001	Any onboard electronic devices must be protected in a way that is waterproof, such that 0 current and no resistance from the	Critical	F-V-001	Dielectric withstand test	Team member(s): Ian
F	The device must be safe to submerge for testing	F-002	The submerged portion of the device must not contain components that would dissolve, deform, or be damaged by water or by contact with water, release pollutants	Critical	F-V-002	Submerge test in small tank at MHL	Team member(s): Ian
		G-001	Device must be structurally stable to test at speeds up to 4 m/s while underwater.	Critical	G-V-001	Analytical analysis	Team member(s): Joel
		G-002	The device may have a cross section no greater than 1m x 0.5m at any point	High	G-V-002	Visual Inspection	Team member(s): Ryan
G	The device must be tested in the MHL tow tank	G-003	The device must use mounting hardware compatible with the MHL tow tank load cell	Critical	G-V-003	Physical application	Team member(s): Alexa

Figure C1a: Validation and Verification Traceability Log

Requirement ID	Verification testing stage	Verification testing date	Verification results summary (2-3 bullet points/sentences)	Verification test conditions	Verification test limitations and uncertainties
A	Plan developed	23-Mar	Results: - To be tabulated	Physical Prototype Evaluation	**Limitation 1**: Functional testing tank size limits flow and hydrostatic pressure conditions. **Solution 1**: Allow for multiple days of tow tank testing, with time to modify the design in between test if necessary **Limitation 2**: Manual Measurement of dimple depth may present measurement error. **Solution 2**: Perform laser testing to determine the relationship of internal pressure and dimple depth.
B	Testing completed	23-Mar	Results: - To be tabulated	Field or Environment Testing	**Limitation 1**: Visual inspection does not quantify steering effectiveness **Solution 1**: Empirical testing should measure lateral forces and from there, steering effectiveness can be determined **Limitation 2**: Tow tank does not allow for free movement of device, which may create challenges for determining steering effectiveness **Solution 2**: Provide future testing suggestions to test dimple depth on turning radius.
C	Method chosen	9-Mar	Results: - To be tabulated	Functional Testing	**Limitation 1**: Visual inspection does not quantify hydrodynamic efficiency **Solution 1**: Aspect ratio measurment and comparison to standard UUV **Limitation 2**: Prototype geometry may change during manufacturing **Solution 2**: Re-measure dimensions after fabrication
D	Method chosen	19-Mar	Results: - To be tabulated	Functional Testing	**Limitation 1**: Static tank testing may not replicate dynamic pressure fluctuations **Solution 1**: Compre actuation pressure to theoretical hydrodynamic pressure. **Limitation 2**: Pressure sensor accuracy may introduce measurement uncertainty **Solution 2**: Calibrate pressure sensor
E	Plan developed	23-Mar	Results: - To be tabulated	Physical Prototype Evaluation	**Limitation 1**: Dielectric test does not replicate long-term water exposure **Solution 1**: Perform repeated trials to simulate longterm water wear. **Limitation 2**: Electrical leakage detectoin may have limitations **Solution 2**: Perform visual check after every testing session and closely monitor pressure sensor to confirm there is no leaking, use calibrated measurement devices
F	Equipment acquired	20-Mar 19-Mar	Results: - To be tabulated	Physical Prototype Evaluation	**Limitation 1**: Faults in construction may arise in the structure as assembly goes on **Solution 1**: Redo test before final assembly **Limitation 2**: Towing tank velocity may considerably affect conditions **Solution 2**: Overspec the construction, and use analytical analysis to confirm that the effects are negligible.
G	Plan developed Testing completed Plan developed	18-Mar 10-Mar 17-Mar	Results: - To be tabulated	Physical Prototype Evaluation	**Limitation 1**: Minor measurement error from manual measurements **Solution 1**: Take measurements using 3D laser scanning **Limitation 2**: Final assembly will not be perfectly uniform throughout due to attachment components. **Solution 2**: Perfrom analysis to determine whether or not surface area of attachment components can be considered negligible.

Figure C1b: Validation and Verification Traceability Log continued

Requirement ID	Verification evidence (use Ctrl+K or CMD+K to hyperlink to respective sheet) - Use V&V Checklist Template sheet	Verification Results	Validation ID	Validation method	Validation question in plain language for sponsors/users	Validation testing owner	Validation testing stage	Validation testing date	Validation test metric + results (2-3 bullet points/sentences)
A	Description of evidence: [insert here]	TBA	A-V	Live demo for sponsor	Is this the scale of dimples that you were expecting?	Team member(s): Ian	Method chosen	30-Mar	Metric: - Sponsor confirmation that dimple depth and appearance match expectations Results: - To be tabulated
B	Description of evidence: [insert here]	TBA	B-V	Showing CAD to Dr. Sareen during meeting.	Is this the expected dimple density/shape/scale?	Team member(s): Ryan	Test data processed	30-Mar	Metric: - Sponsor confirmation that actuation configuration appears capable of enabling stearing Results: - To be tabulated
C	Description of evidence: [insert here]	TBA	C-V	Live demo for sponsor	Is this the shape you were expecting?	Team member(s): Ryan	Method chosen	19-Mar	Metric: - Sponsor approval of vehicle shape Results: - To be tabulated
D	Description of evidence: [insert here]	TBA	D-V	Live demo for sponsor	Will this level of actuation classify as negligable?	Team member(s): Alexa	Method chosen	26-Mar	Metric: - Sponsor confirmation that actuation pressure threshold prevents accidental actuation Results: - To be tabulated
E	Description of evidence: [insert here]	TBA	E-V	Live demo for sponsor	Would this be classified as normal conditions?	Team member(s): Joel	Method chosen	30-Mar	Metric: - Safety compliance for electrical systems near water are confirmed Results: - To be tabulated
F	Description of evidence: [insert here]	TBA	F-V	Conference with MHL staff	Is this vessel safe to submerge?	Team member(s): Ian	Method chosen	27-Mar 26-Mar 25-Mar	Metric: - Confirm prototype safety compliance for electrical systems near water Results: - To be tabulated
G	Description of evidence: [insert here]	TBA	G-V	Listing testing details for Dr. Sareen	Is this suite of testing sufficient for our needs?	Team member(s): Joel, Ryan, Alexa	Method chosen	18-Mar 24-Mar	Metric: - Sponsor and stakeholder approval of test plan and structural integrity of the prototype Results: - To be tabulated

Figure C1c: Validation and Verification Traceability Log continued.

Requirement ID	Validation test conditions	Validation test limitations and uncertanties	Validation evidence (use Ctrl+K or CMD+K to hyperlink to respective sheet) - Use V&V Checklist Template sheet	Validation results
A	Prototype submerged in MHL small tank under static water conditions	**Limitation 1**: Demonstration occurs without hydrodynamic flow **Solution 1**: Secondary validation during towing **Limitation 2**: Sponsor judgement is subjective **Solution 2**: Provide measured dimple depth data from laser testing.	Description of evidence: [insert here]	TBA
B	Prototype review meeting	**Limitation 1**: Steering performance is not directly demonstrated **Solution 1**: Validate during tow tank experiments **Limitation 2**: Prototype geometry may not be exact in manufacturing **Solution 2**: Re-measure dimensions after fabrication.	Description of evidence: [insert here]	TBA
C	Prototype review meeting	**Limitation 1**: Validation is qualitative **Solution 1**: Provide dimension comparisons to standard UUV aspect ratio **Limitation 2**: Prototype may be missing some final components **Solution 2**: Provide prototype images during tow tank testing.	Description of evidence: [insert here]	TBA
D	Prototype review meeting	**Limitation 1**: Velocity effects may be large. **Solution 1**: Validation during first day of testing and overspec design **Limitation 2**: Dr. Sareen may not be able to tell just by looking if the depth is small enough at idle. **Solution 2**:Laser testing with glass aquarium tank.	Description of evidence: [insert here]	TBA
E	Functional testing and prototype review meeting	**Limitation 1**: Testing occurs in a controlled tank may not fully represent real underwater operating conditions like debris or deep-water pressure levels and associated fatigue **Solution 1**: Conservative pressure levels during testing can be compared to the results of future tests. **Limitation 2**: Validation relis on sponsor opinion **Solution 2**: Document pressure levels to catch any skin fatigue early, preventing possible punctures and damage to electrical equipment	Description of evidence: [insert here]	TBA
F	Prototype review meeting	**Limitation 1**: This test rig has different features than any other rig tested by the MHL staff **Solution 1**: Communicate the objectives and concepts with the MHL staff **Limitation 2**: Conditions may change as final assembly develops **Solution 2**: This test will be redone after final assembly.	Description of evidence: [insert here]	TBA
G	[insert conditions]	**Limitation 1**: Analytical assumptions used in structural evaluation may simplify flow conditions **Solution 1**: compare analytical predictions with experimental data **Limitation 2**: Validation relies on sponsor opinion **Solution 2**: Provide objective data and other analytical predictions to confirm that prototype is ready for the MHL tow tank	Description of evidence: [insert here]	TBA

Figure C1d: Validation and Verification Traceability Log continued.

Appendix D: User Guide

Spring 2026 ME450 Submersible with Morphable Skin Control System

Purpose:

This document is intended to document the use and operation of the pneumatic vacuum system and code from the 2026 spring ME 450 project, tasked with designing a morphable skin-equipped submersible test device.

Code:

Normal Operation:

Lines 1-10 contain the changes that you may wish to vary throughout experimentation. Under normal operating circumstances, you should not have to change anything outside of this range. These conditions assume a realistic device with some amount of leak present.

`PressureLeftSetPoint` & `PressureRightSetPoint` set the desired pressure on either side of the submersible. Set these values in units hPa.

`ErrorbandTight` controls how tight of a deadband in hPa must be reached before the system is allowed to enter the sealed state. This is functionally a +/- range to target if you set `ErrorbandWide` to 0.

`ErrorbandWide` controls the range, in addition to `ErrorbandTight`, in which the system may remain in the sealed state. This adds stability to the measurements and prevents the system from oscillating around one pressure boundary.

`PulseDelay` is the time, in milliseconds, that the system requires to pass before pulsing the solenoids, and double the time between sampling data. This may be manipulated, but for most practical applications, the default value of 1 is sufficient.

Error messages and live data updates can be seen in the serial monitor, and the serial plotter will show a live graph of the value of pressure on the left and right sides in hPa.

If the device operates for an extended period and stops working, 20-40 minutes, it likely ran out of allotted memory. You may repush the code, and it will reset this behavior. Generally, this is only applicable when showing for presentations or demonstrations, as very few trials will require that extended test window.

Ideal Operation:

If you are operating an ideal device, with no detectable leakage and sufficient control volume, it is recommended to make the following changes to the code:

Set lines 50 & 68 to read `HIGH` as their output. This will change the behavior from sealing the values in the vent state and allowing the leak to lower pressure to having active pressure venting.

Occillations:

Frequent oscillation of pressure or rapid clicking of the solenoids is observed; there are 3 possible solutions. The first, and most preferred, would be to implement additional control volume into the system to dampen pressure changes and decrease the rate of pressure change. There is a PTC valve on each side where a secondary control volume tank may be added. The second solution is to increase your error bands, which stabilizes oscillating behavior but increases error bars in your measurements. The third option, which is not generally recommended, is to reduce error bands to 0 and change the operating commands to always seal in any state but pumping, which will result in large amounts of overshoot, but significantly reduced oscillations. This is similar to setting an upper limit on pressure that must be met before pumping begins again.

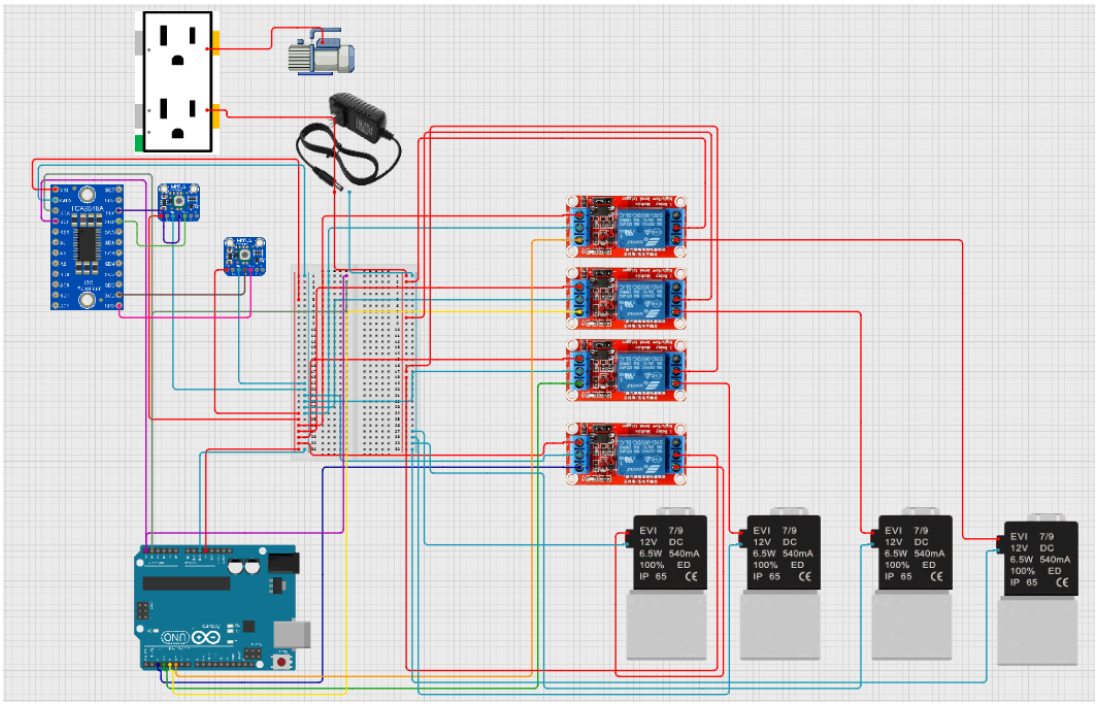
Failure to detect a Pressure Sensor:

If you receive an error message that says the Arduino has failed to communicate with a device or could not find a device, please check the wiring of the board. It is very likely that a jumper has been knocked loose. Consult the wiring diagram below

Electronics:

Wiring Diagram**:**

A complete wiring diagram can be found below. Please consult while attempting to troubleshoot any electrical issues.



Heat:

Both the pump and solenoid values tend to operate at elevated temperatures, ~130F. They are designed as such and this should not be a major concern. Optionally, a tabletop fan may be placed near the solenoids if they are operating for prolonged periods of time to cool them, however the pump is most efficient when working at these temperatures.

Power:

To operate the device correctly, the wall adapter for the solenoids and the pump must be plugged into the wall, and the Arduino must be plugged into a laptop. The laptop need not be actively running code, and will run the last pushed program, but the Arduino must receive power over USB to actuate the relays.

Pneumatics

Device installation:

Connect each side of the test device using a run of ¼” OD PTC pneumatic tubing to either of the PTC valves at the end of the pneumatic system, ensuring that one goes to the left and one to the right side of the system.

If extra control volume is desired, it may similarly be installed on the second PTC valve on each side, otherwise this may be used as a manual relief valve for the system.

Ensure that the valves are set to your desired state, with open being parallel to the flow of air and closed being perpendicular. If the valves are in the wrong state, either the vacuum won't reach your device, or it will have direct access to the atmosphere.

Ensure you connect the desired "left" and "right" sides appropriately. Both the solenoids and gauges are labeled with the side to which they belong.

Gauges:

A glycerin pressure gauge is outfitted on each side and labeled. Please ensure that when you set up the system that gauges are positioned in a convenient way to read. The PTC connectors can twist to accommodate different table setups.

Appendix E: Project Timeline

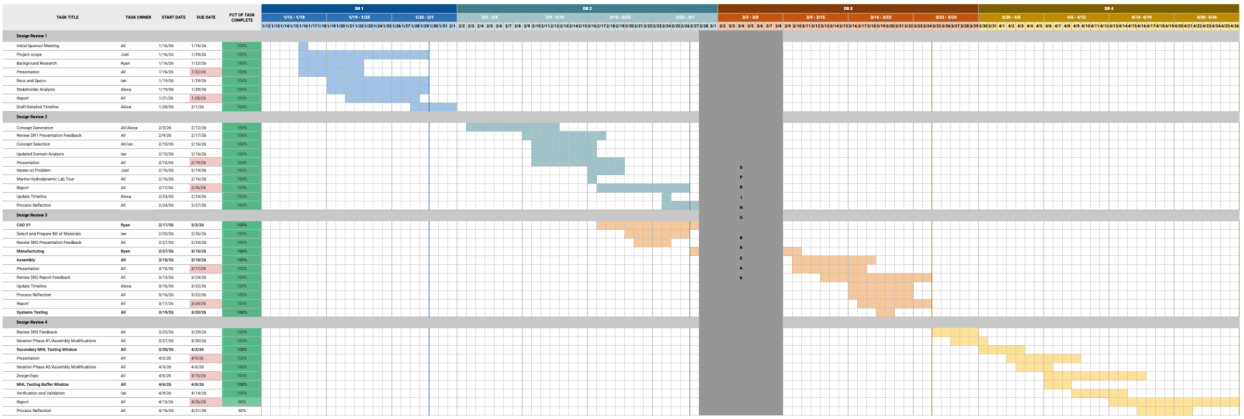


Figure E1. This gantt chart shows the scheduled progression of the project over the Winter 2026 semester. A view-only copy of this chart can be found here if visibility is difficult.

Appendix F: Build & Design Purchased Bill of Materials

adafruit	digital pressure sensor	3965	2	$29.95	$59.90
amazon	1/4" ptc toggle valve 5 pack	B0D5Y1XWDX	1	$11.99	$11.99
amazon	-30 to +30 psi gauge	B08ZHXFYKN	2	$9.93	$19.86
amazon	1/4 HP vacuum pump	B0CSGDHQML	1	$62.99	$62.99
amazon	1/4" npt to 1/4"npt Fem-Fem coupling 2 pack	B082V8FJQJ	1	$4.99	$4.99
amazon	Marine epoxy 2 pack	B0CT996CM2	1	$13.58	$13.58
amazon	PTC connector kit	B07RSLDDBR	1	$12.99	$12.99
amazon	2/2 solenoid valves	B0FH78JRQ8	4	$12.48	$49.92
amazon	Arduino Uno	B008GRTSV6	1	$27.60	$27.60
amazon	breadboard + jumpers	B08Y59P6D1	1	$9.99	$9.99
amazon	12V relay 4 pack	B095YFJ69T	1	$6.99	$6.99
amazon	120AC to 12V dc converter	B01GD4ZQRS	1	$7.89	$7.89
amazon	ptc secondary fittings kit with screw attachments	B0FH4RZ4GV	1	$16.99	$16.99
Mcmaster	1/4" OD Pneumatic Tubing	5648K31	1	$21.50	$21.50
Mcmaster	3/8" universal to 1/4" ptc	7699N18	1	$4.72	$4.72
Mcmaster	1/64" 50A neoprene sheet	1374N31	1	$15.60	$15.60
Mcmaster	.01" rubber sheeting-42" x 2ft long	8611K13	2	$12.00	$24.00

Table F: Complete BOM of purchased materials for this project

Appendix G: Manufacturing/Fabrication Plan

All of the pieces to this project are 3D printed. A print bed of the size 325 mm x325 mm x350 mm is required to actually print these items, this is because of the large size of the prints. The ideal print settings for the overall project are:

- ABS/ASA Filament

- 0.6 mm nozzle
- 0.3 mm layer height
- 4 walls
- 4 top/bottom layers
- Gyroid infill @ 8%
- Tree supports w/ support material as the interface layer

Each of the parts are oriented on the build plate in a way that allows for the most optimal print. The hulls stand vertical so that there is no required support, the actual center connection piece prints upside down in order to allow for good bed adhesion, and the foil connector pieces can print in the standard orientation. All of these orientations can be seen in Figure ll.

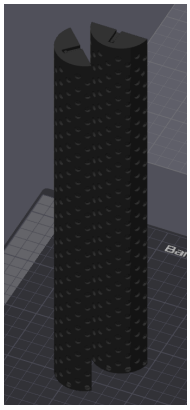
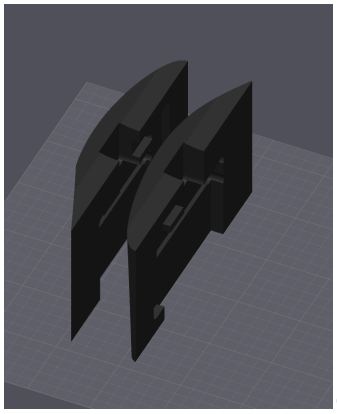
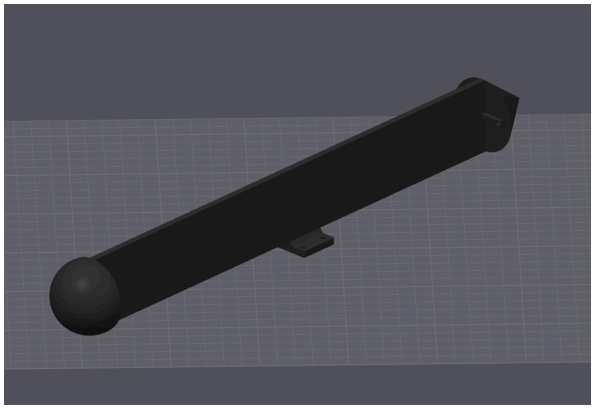
a.)  b.)  c.) 

Figure ll. The different parts of the assembly are shown in their ideal print orientation..

Team Biographies

Joel Bhattarai:

Joel is a mechanical engineering senior at the University of Michigan. Joel grew up in Novi, Michigan, and has had a passion for learning how everything and anything works and being able to optimize and redesign products to maximize results. Joel has supplemented his studies through NASA's L'SPACE program completing both the Mission Concept Academy and NASA Proposal Writing and Evaluation Experience as Lead Systems Engineer and Principal Investigator respectively. Joel hopes to enter the workforce as a mechanical controls engineer, continuing his interest in dynamics and control systems.

Ian Carter:

Ian is a mechanical engineering student who grew up in Chelsea, Michigan, and will be graduating in May. Ian has always had a passion for creating, innovating, and understanding the world around him which lead him towards mechanical engineering. He plans to go into the private workforce after graduation, likely with a focus on industrial and biomedical manufacturing. In addition to his regular coursework, Ian works in the EMBiR lab, which is focused on using biology to inspire robotics and

robotics as a method to study biology and evolution, in particular working on a robot that models the dynamics of a snake bite and envenomation. Beyond the university, he runs a combat robotics team, or miniature battlebots, which compete across the northeast. He also volunteers as a coach for a high school robotics team, teaching CAD, design for manufacturing, and strategic design.

Ryan McGlynn:

Hailing from Cottrellville Township, MI, Ryan McGlynn is a Mechanical Engineering senior at the University of Michigan who approaches engineering design as a creative challenge. His obsession with learning how things function and how to make them better lead him to pursuing a degree in mechanical engineering. His technical background includes developing closure systems at Scout Motors and designing aerodynamic components for the UMich Supermileage team where he competes in the Shell Eco-Marathon. Beyond the engineering lab, Ryan loves music and even competed in DCI as a member of Legends Drum and Bugle Corp. He also has a deep passion for photography, videography, and wildlife. He intends to apply his blend of technical discipline and creative curiosity to a career in automotive studio engineering.

Alexa Remirez-Greenwood:

Alexa Remirez-Greenwood is a senior Mechanical Engineering student at the University of Michigan with interests in dynamics, controls, and naval engineering systems. Her work emphasizes hands-on analysis and testing of dynamic mechanical systems. In addition to her technical coursework, Alexa serves as a Student Manager at the Student Organization Resource Center where she oversees daily operations, processes billing, and manages daily communications with clients. She is also pursuing a minor in Music, which inspires her unique and creative approach to problem-solving. After graduation, Alexa plans to pursue an entry-level mechanical engineering role working on complex mechanical systems.