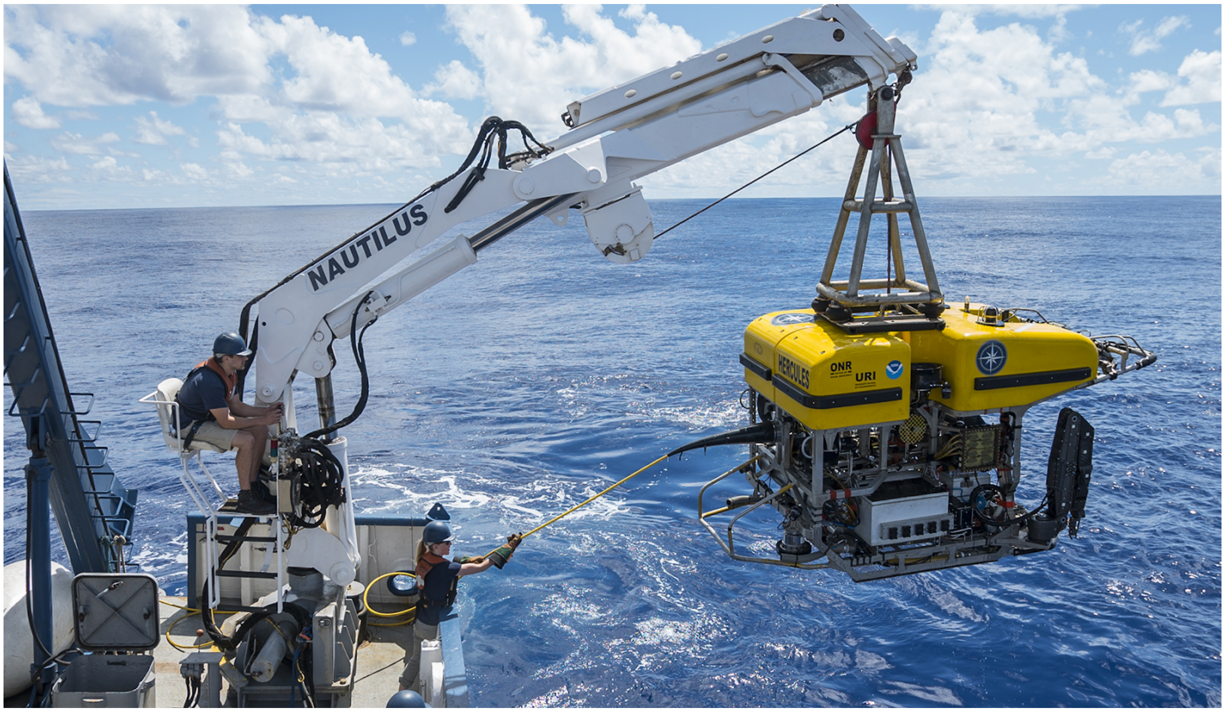
ME 450 Fall 2020 Design Report

Team 6: Robotic Marine Exploration



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Executive Summary

According to the latest decadal survey of ocean science, the geographical, chemical, and biological character of the subseafloor environment and how it affects global elemental cycles and understanding of the origin and evolution of life, is an important and largely followed research direction in recent years. The sea floor is the deepest part of the ocean where natural resources are abundant and mysterious creatures reside. However, only a fraction of the ocean floor has been mapped and there is a high cost, inefficient exploration method, and risky environments as obstacles in the way of ocean mapping research. Each member of this project team has a passion and interest for marine exploration and we are motivated to design an underwater robot with a high quality seafloor mapping ability at a lower cost to support marine exploration. The specifications of our proposed design is benchmarked against a commercialized existing solution, the Bluefin HAUV. The design specifications are as follows: must be able to map the seafloor at a resolution of 0.25m with the speed of 0.5 knots, cost less than $70,000, operate for at least 3.5 hours and at a depth of up to 30 meters and at a temperature of up to -2 °C, all while operating at a sonar frequency outside of the 30 Hz to 8 kHz range that ocean wildlife communicate at.

Using these requirements and specifications, our team identified and separated the major systems of a typical AUV and generated a list of all possible concepts through a combination of brainstorming, design heuristics, and morphological analysis. These concepts were then evaluated mainly by doing additional research, comparing the advantages and disadvantages against each other, and checking whether each concept is able to sufficiently fulfill the requirements and specifications. Through this process, we selected an AUV design that has a submarine-like shape but with additional dolphin-inspired parts, a lithium ion battery as its power source, a side-scan sonar system as a mapping tool, a multiaxial propeller(s) as the kinematic system, and an airbag feature as the emergency mechanism in case of water leakage inside the robot.

After the concept exploration, the detailed design and the analysis were done on each subsystem to ensure its validity. The shell is designed to have a small drag coefficient and large pressure resistance. For the kinematic system, one unique design is to tilt the robot so that the robot could move up or down instead of spiraling. Battery selection considers low costs and relatively high power capacity as the two primary considerations. The waterproofing design ensures that our robot will remain watertight 30 meters underwater. And the overall design can withstand a temperature under 0 degrees Celsius with all materials and components costing approximately $20,000.

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Problem Description and Background

Background

As of June 2020, only 13.7 percent of the ocean floor has been mapped at a resolution of one kilometer using sonar technology [2]. Seafloor mapping allows us to explore and potentially exploit earth's natural resources from the ocean, while also preventing disruption to the ocean wildlife. The benefits of mapping the ocean floor include gathering biological research information involving the origins of evolution and behavioral data of unknown fish species, locating underwater landslides to prevent natural disasters, determining the layout of undersea cables for telecommunication and data transfer, and gathering precious metals and fossil fuels.

As estimated by the Nippon foundation [2], the current time and cost of mapping 100 percent of Earth's ocean floor is approximately 350 ship years and three billion dollars, respectively. However, through the utilization of several low-cost robots fitted with active sonar devices, the time and cost to map the complete ocean floor are reduced significantly. Our project goal is to design an underwater robot that maps the seafloor in hopes of eventually creating a map of the entire ocean floor.

Benchmark

There are two types of underwater robots: AUVs (autonomous underwater vehicle) and ROVs (remote operated vehicle). Bluefin HAUV [3] is one of the existing solutions in the market and is manufactured by Bluefin Robotics. Bluefin HAUV is not the flagship version among various AUVs constructed by Bluefin robotics, but it is a good benchmark since it is an underwater robot which has been proven to work in the conditions and parameters needed for high quality seafloor mapping. Bluefin HAUV is also an AUV, which has a lower cost of operation compared to an ROV but is much more complex and expensive and not necessary for seafloor mapping [3].

Figure 1. Image of Bluefin HAUV [3] developed by Bluefin Robotics.

Requirements and Specifications

The requirements and specifications for our project are outlined in table 1 below.

Table 1. Summary of the user requirements and engineering specification.

Requirements	Specifications
Quickly obtain a high quality seafloor map	• Able to move at 0.5 knots (0.257m/s) and still get resolution along the direction of movement at 0.25m • Coverage area/h: 0.20 km^2/hr • Be able to detect seafloor 90m below the sea surface
Inexpensive	• Total price can not exceed $70,000
Durable	• Must be able to operate for at least 3.5 hours with all components being constantly powered • Must be able to remain waterproof submerged in saltwater up to 30 meters for at least 3.5 hours • Must be able to operate up to -2 °C
Harmless to wildlife	• Does not use a sonar frequency between 30 Hz and 8 kHz

The requirements are listed in order of highest priority to lowest priority descending. The user requirements have been translated into engineering specifications so that we could test if we fulfilled the requirements during the design process. These requirements and how we derived their corresponding specifications are explained in the next sections of the report.

Quickly Obtain a High Quality Sea Floor Map

According to research based on the Seabed 2030 initiative [2], which hopes to map 100 percent of the ocean floor by 2030, only 13.7 percent of the ocean floor has been mapped to a resolution range of 1500 meters whereas 76.3 percent of the ocean floor has been mapped from a range of 3000-5750 meters. The current market for underwater robotic marine exploration is saturated with robots which are focused in the deeper 3000-5750 meter depth range. Since this depth range requires the robot to go deeper into the ocean, the robot also needs to be more durable and a more powerful sonar device is required to map the seafloor at a high quality resolution. These conditions invariably increase the price of the robot and are not necessary to obtain the benefits mentioned in the background section of this report (page 3). The conclusion is that there is a real need and focus among researchers to create a less expensive robot that can map the seafloor at a depth up to 1500 meters.

From our research we found that the general sonar resolution with moderate speed and distance between objects can be below 0.5 m (Shown in Figure A.2). This high resolution enables the robot to detect and even identify some mine-like objects (Shown in Figure A.3). For our project, the robot will focus on detection instead of identification since this robot is expected to map the seafloor and it is expected to classify mine-like objects at a minimum. This is the reason that the first specification sets the speed of the detection and accuracy of the sea-floor mapping. The speed specification is derived from our benchmark of 0.5 knots (see Figure A.1). Figure A.2 further justifies 0.5 knots that could give us enough resolution to detect targets (shown in Figure A.4). The 0.25m resolution specification is from Figure A.3 where the software used will be able to classify both mine-like objects and non-mine objects at a 99.6% accuracy. The coverage area per hour specification is derived from the speed and the detection width of 500 m, which is a high standard specification that comes from the average detection width of a side-scan sonar, one of the sonar types that gives the largest coverage area. The resources in the shallow water are more accessible but also require more evaluation. We hope our AUV could help the process of evaluating resources accessibility in the future.

Inexpensive

This requirement comes from the need to lower the three billion dollar estimated cost of mapping 100 percent of the ocean floor, which we hope to achieve by designing a low-cost underwater robot to do this. The specification related to the inexpensive requirement was chosen to be a purchase price that does not exceed $70,000 to the end user. Based on research conducted by the USF College of Marine Science [4] it was determined that the average cost to build an underwater robot unit is $70,000 US dollars. If we can reduce the total cost of the robot to the end user, we will have made the robot less expensive and thus fulfilled this requirement.

Durable

It is important that our robot can withstand the environmental conditions in the ocean such as high pressure and salt water corrosion. Additionally, two of our specifications to fulfill this requirement is that the robot can fully operate for at least 3.5 hours and that it can operate at a depth of up to 30 meters in saltwater. These specifications were chosen because our benchmark robot unit, Bluefin HAUV [3] (which we took to be a rough industry standard), had a maximum operation time of 3.5 hours and a depth rating of 30 meters. If we are able to increase or match both the duration time and depth rating compared to the benchmark, we will have increased the rough industry standard and thus made the robot more durable. Another specification chosen was that the robot must be able to operate at a temperature of up to -2 °C as the coldest regions of the ocean are located in the arctic circle where the surface water of the Arctic Ocean is fairly constant at approximately -1.8 °C [5] which we rounded up to -2 °C for safety purposes.

Harmless to Wildlife

One of the benefits of seafloor mapping is to help with ocean and wildlife conservation. In doing so, this requirement ensures that the robot designed will not harm the existing ocean wildlife population. Upon further research we found out that one of the ways that we could potentially be harming wildlife is by disrupting whale communication. Whales communicate at frequencies ranging from 30 Hz to 8 kHz [6] and sonars operating within this frequency range can disrupt their communication. Sonars are able to operate anywhere from infrasonic frequencies at around or below 20 Hz, to ultrasonic frequencies up to 20 kHz [7].

Concept Generation

With the requirements and specifications in place, our team entered the concept exploration phase where we generated and developed different concepts for the robot that could potentially meet some or every requirements and specifications. In order to generate enough ideas to effectively select the best concept that will meet our requirements and specifications, we utilized different methods and tools of divergent ideation. Because our team will be building an underwater robot from scratch, we need to consider every crucial component and system for an underwater robot with sonar-mapping capabilities. To do this, our team performed functional decomposition and determined the most important systems in a typical AUV, which includes design/shape, power source, sensors, kinematic systems, components' protection, inner structure, material and other miscellaneous systems for our robots (e.g. deployment systems, mechanism for warding off predators, control method). Once determined, we then divide each system down into several categories for which each idea generated under these systems can be categorized into before generating and listing as many concepts possible that fall within these categories. The concept flowchart in Figure 2 summarizes the method of divergent concept generation described for coming up with a list of initial concepts as described, where the orange boxes represent the major systems obtained from functional decomposition, the yellow boxes represent the categories of ideas under each system (orange boxes), and the blue boxes represent all the ideas that have been developed and to which category (yellow boxes) and systems (orange boxes) they are categorized into.

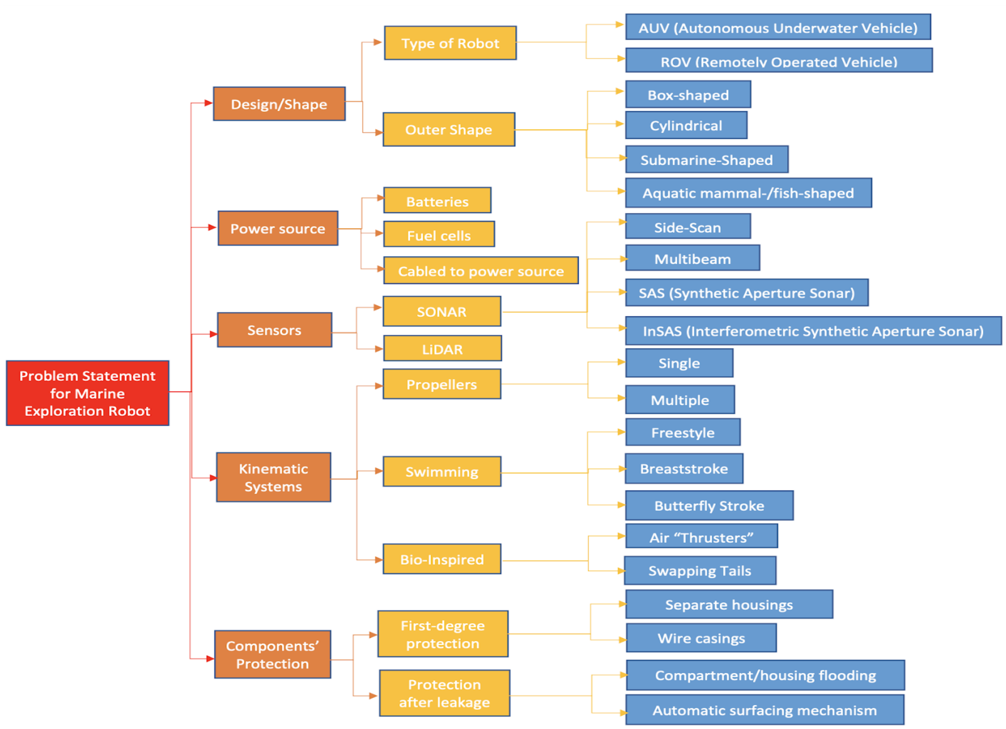


Figure 2. Concept exploration plan layout

As shown in Figure 2, our concept exploration ensured that we have a good problem definition with concrete requirements and specifications before expanding out into looking at individual solutions for our design specifications. Figure 2 is meant to visualize our progress through the divergent ideation process to generate our list of concepts and not to show our entire list of concepts, which is why only the most important and significantly different systems, categories, and concepts were listed. A complete list of all the systems and ideas generated for the divergent ideation stage is shown in Appendix B. We mostly brainstormed as a group and encouraged wild ideas to come up with our list concepts, but a few were determined using concept developments of design heuristics and morphological analysis as well. The detailed specifics on how we developed these concepts and converged on ideas and evaluated and selected them are explored more in depth in the following Concept Development and Concept Evaluation/Selection sections.

Concept Development

After generating our concepts, we began exploring and researching the validity of these concepts for the different parts and systems of our underwater robot design. These include the overall shape of the robot, the sonar sensors and the kinematic system.

Design/Shape

As mentioned earlier, there are only two types of underwater robots: AUV and ROV. The advantages of an AUV over and ROV include being more efficient and less labor intensive and less expensive overall. These advantages far outweigh the disadvantages which are the complicated software and sensor systems required to operate an AUV.

From our meeting with Professor Vasudevan, he encouraged us to take a more practical approach with our project and assured us that it is more than reasonable to design only the mechanical aspects of an AUV since our team is composed mainly of mechanical engineers. Therefore, we decided to model our project around an AUV.

Sensors

The concept development process for the sensor systems of the underwater robot, our team primarily used brainstorming methods incorporating our previous knowledge and research of commonly used sensors on underwater vehicles, along with ideas of other known sensors that may be beneficial to an underwater autonomous vehicle. Our developed concepts primarily included sensors related to positioning and navigation along with seafloor mapping/depth detection sensors, but also included some other sensors with unique purposes and use cases. Table 2 below lists our developed concepts with a brief description of each.

Table 2. Concept development for sensor systems

Sensor Concept	**Description**
Inertial Motion Unit (IMU)	Sensor used for determining vehicle orientation through use of accelerometers, gyroscopes, and sometimes magnetometers.
Doppler Velocity Log (DVL)	Sensor used for measuring motion relative to seafloor.

Depth/Pressure Sensor	Sensor used to measure the depth/pressure experienced by the underwater vehicle, useful for positioning and ensuring safety.
Relative Position Sensor (Hull-relative or seafloor-relative navigation)	Sensor provides the robot position relative to the deployment vessel or seafloor (device dependent). This sensor is useful in robot positioning.
Global Positioning System (GPS)	Satellite-based navigation/positioning system
Sonar	Used for depth measurement and seafloor mapping. Emits acoustic waves and detects the waves upon return, using the acoustic wave behavior and return time to determine seafloor depth. Many variations of sonar technology exist.
Light Detection and Ranging (LiDAR)	Used for depth measurement and seafloor mapping. Emits laser pulses and detects the returning light, measuring depth based on return time.
Moisture Sensor	Detects any water breaching vehicle hull, triggering a possible safety/recovery system.

These listed concepts show the concept development that was done related to the sensors to be included on the robot. Further discussion of the drawbacks and benefits of each concept, along with explanation of the sensor concept evaluation process can be found in the Concept Evaluation/Selection - Sensor subsection of this report (pages 11-14).

Kinematic Systems
To visualize how we developed the kinematic concepts, a concept map is shown in Figure 3.

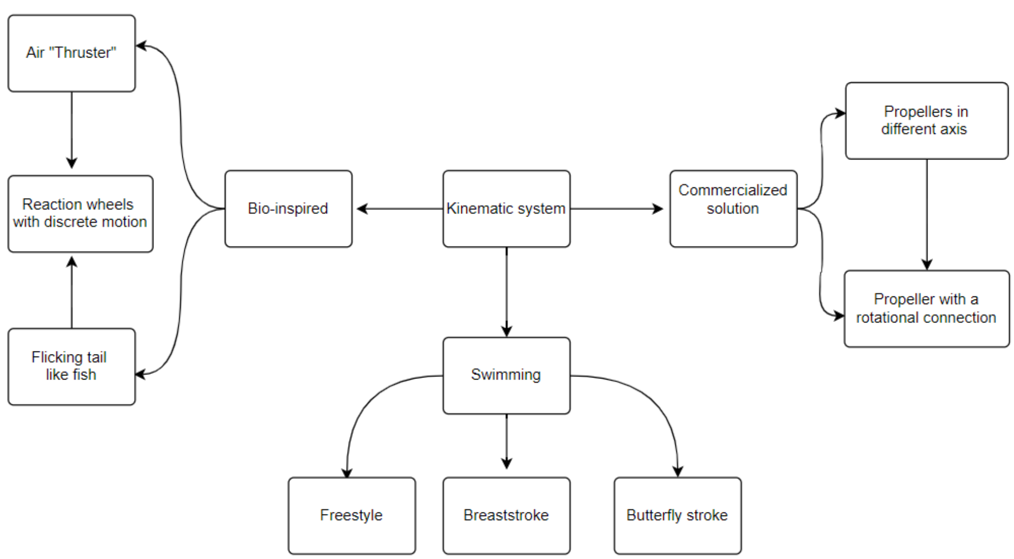


Figure 3. Concept flow chart for kinematic system

There are three layers in this map. The first layer is the subsystem we are doing. The second layer is where these concepts were generated. The last layer is the concept. Layers are connected to each other with arrows. Also there are arrows between concepts. These arrows represent how concepts are developed. In this section, design heuristics is used to develop concepts. For instance, we used the design heuristic of mimicking natural mechanisms to derive bio-inspired and swimming concepts. However, we realized that these would cause severe imbalance in the body. Therefore, we applied the design heuristic of using an existing mechanism in a new way: reaction wheels. Reaction wheels are good at self-orientation without any external force. With a well tuned control system, the robot will be able to adjust orientation right after one discrete motion and do another.

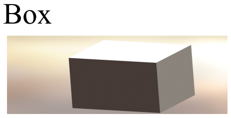
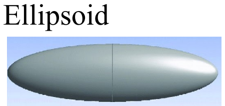
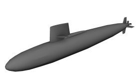
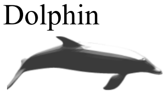
Concept Evaluation / Selection

After evaluating and generating the different concepts for our design, we began narrowing down the different concepts and determining which were the most viable and best choice through comparisons based on our specifications, research, and engineering analysis.

Design/Shape

Table 3 shows two ends of a complexity spectrum in reference to some of the shapes we considered to enclose our robotic unit. The top of the spectrum is the least complex while the bottom of the spectrum is the most complex. We incorporated the drag coefficient, the feasibility of manufacturing, a rough cost multiplier, and the novelty of the idea into account.

Table 3. Prospective Design Analysis of possible housing shapes.

Design Description	**Drag Coefficient**	**Manufacturing Feasibility**	**Rough Cost Multiplier**	**Novelty**
Box 	2.1	10	1X	8
Ellipsoid 	0.07	8	4X	4
Submarine 	0.35	6	5X	3
Dolphin 	0.0036	1	10+X	10

A low drag coefficient reduces aerodynamic drag. Drag is a significant component in power loss and scales exponentially with velocity. Our durability specifications require an operating time of at least 3.5 hours and the robot may operate at higher speeds during that operating time. Reducing any power loss within our robot will help us fulfill this specification.

The feasibility of manufacturing is based on the shape of the concept and the estimated time it would take to make each part and put it together, with 1 being the most difficult and 10 being the most feasible. The rough cost multiplier and manufacturability are based on the curvature of the shape, the number of parts the shape has, and most importantly the total time it would take (and labor intensiveness) for each end-product shape. All of these were considered ultimately to make sure we are actively trying to fulfill the requirement that the robot will be cost-efficient as explained for each shape in detail below.

The novelty factor was also added because we wanted to make something new. We didn't want to just create something that is essentially a clone of the existing solutions. The "novelty" factor was based on team input and the qualitative frequency of each general shape in research and industry applications.

Let's start with the least complex shape we considered, the box-shape with a manufacturing feasibility ranking of 10 and cost multiplier of 1X. This shape was determined to be quite easy to manufacture since it had the least number of parts with only 6 sides, the least amount of curvature for each part (none), and the lowest labor intensivity to create the shape (around 20 minutes per side). It was used as the baseline for our cost multiplier and determined to be the cheapest option for manufacturing. The novelty factor of this was determined to be an 8 out of 10. The reason we ranked it so high was because we found no other commercial existing solutions that had a simple box shape (and as we will later find out, for good reason). The drag coefficient was significantly higher than the rest. Although the novelty factor was high, it was in the form of infrequency of application and laziness rather than innovation.

Next, we considered a slightly more complex ellipsoid-like shape with a manufacturing feasibility ranking of 8 and cost multiplier of 4X. This shape was only slightly harder to manufacture due to the increased curvature involved in the shape (medium amount), same number of parts as the box (6 parts), but much higher labor intensivity (around 45-60 minutes per part). All of these factors contributed to the rough cost being four times our baseline since we based cost on curvature, labor intensivity, and number of parts. The novelty factor was quite low, we determined it to be a 4 on our scale because although this shape specifically did not show up in application, many shapes very similar to it showed up in application. The drag coefficient was significantly reduced to just 0.07 since it is a perfect ellipsoid even though it isn't perfectly practical, it was considered.

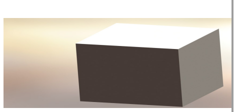
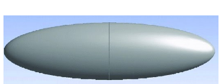
Then came the most common streamlined body-like shape in the underwater vehicle world, the submarine with a manufacturing feasibility ranking of 6 and cost multiplier of 5X. The feasibility of manufacturing only lowered slightly since this streamlined body is essentially a deformed ellipsoid with extra parts. The same figures for curvature (medium) and labor intensivity (45-60 minutes per part) were used as in the ellipsoid-like shape but with an increased number of parts. The rough cost multiplier was also not much more than an ellipsoid because a few small extra parts would be added. The novelty factor was low at only 3 because this solution is long in the tooth. Most underwater vehicles look similar to this. The drag coefficient was reasonable, it was higher than the unobtainable perfect ellipsoid shape but significantly lower than the box-shape.

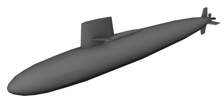
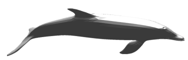
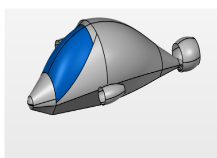
The most complex body we considered was that of an actual dolphin for our robot enclosure with a manufacturing feasibility ranking of 1 and cost multiplier of 10+X. Although this robot would be next to impossible to create due to its cost and manufacturability, we wanted to consider it because it was a novel idea. The factors that contributed to the cost and manufacturability were as follows: level of curvature (high), labor intensiveness (60+ minutes per part), and sheer number of parts (possibly over 50). This was a very wild idea rated at 10/10 on our novelty scale since it had not been done before in reference to underwater seafloor mapping. The added benefit was that this shape had an unimaginably low drag coefficient at just 0.0036. The only other shape (even in the experimental world) that we found to have a lower drag coefficient was a flat plate under laminar flow. This shape has its downfalls but it definitely has its benefits as well.

This is why our final design will look something similar to this. It's essentially a streamlined body shape like a submarine with added dolphin-like features such as fins, a more pointed nose, or possibly a tail. We found that the reduction in drag coefficient while adding minimal dolphin-like features was worth the incremental cost and lower manufacturability of the robot. In addition to this, we gave it a novelty rating of 7 since we often see aerodynamically-inclined shapes in the underwater robot world, but none of them dolphin-inspired.

This shape keeps costs down at being only slightly higher than the enclosure for a submarine-like shape while also reducing power loss through the reduction of the drag coefficient and keeping a relatively high manufacturability and high novelty! The summary of this paragraph is in table 4 below.

Table 4. Weighted Pugh chart for comparing the major generated concepts for the robot shape.

Concepts	**Drag Coefficient**	**Feasibility of Manufacturing** *based on complexity of shape, time it would take to make each part (10=high, 1=low)	**Rough Cost Multiplier** *based on curvature and number of parts	**Novelty** *based on team input and qualitative frequency in research (10=high, 1=low)
	2.1	10	1 X	8
	0.07	8	4 X	4

	0.35	6	5 X	3
	0.0036	1	10+ X	10
	<0.35	5	6 X	7

Robot Housing Shape Analysis
The shape of the body enclosing the robot's subsystems will resemble a streamlined body while trying to incorporate dolphin-like features if manufacturing costs, stability, and robotic movement are not severely negatively affected in reference to the benefits added.

After some CFD analysis completed through Ansys Fluent, we obtained data to evaluate whether or not our design would satisfy our requirements and specifications, namely, the specifications under the "Durable" requirement. The mesh had a quadratic element order, resolution of 4/7 and medium smoothing quality. Given the computing power we had, these were ideal qualities since they provided reasonably interpretable visual and computational data without excessively straining the computer used for the CFD tests.

The points of interest we wanted to explore were the drag value and velocity and pressure contours. Ansys stated that the pressure and velocity plot results converged for our solutions given the quality of the mesh at one-hundred-fifty-nine iterations for the velocity and pressure as shown in Figure 4. Ansys also stated that the drag coefficient simulations converged, although a bit untidily, at seventy-seven iterations as shown in Figure 4. Convergence of the data confirms the reputability of the results given the sophistication of technology and methods used.

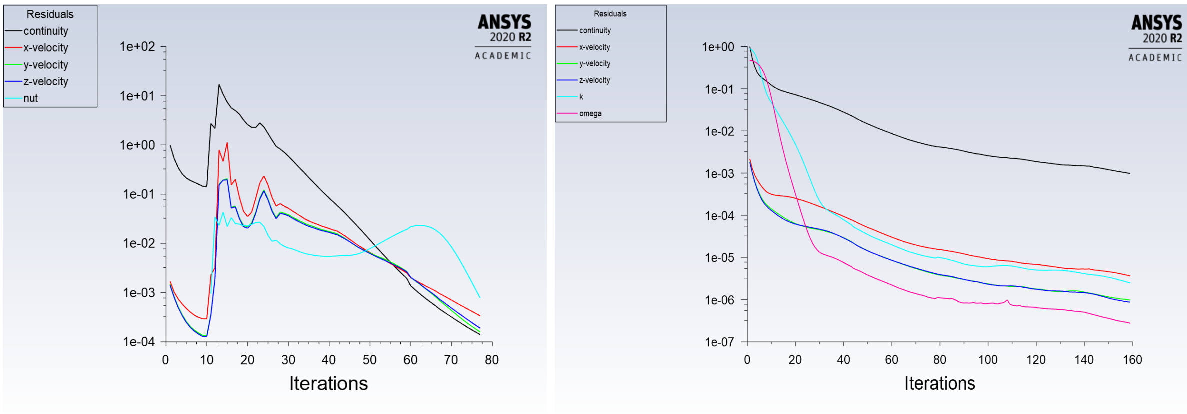


Figure 4. Residuals for the SA drag model (left) and SST KΩ contour model (right).

To obtain the drag coefficient, a Vorticity-based Spalart-Allmaras turbulence model was used with air being the acting fluid material. This model was used for drag because it provides quick convergence of data while staying fairly robust when compared with real-life applications. Because SA converges quickly, the computer we used to do CFD on the housing shape would not strain the computing power of our technology too extremely. In addition to quick convergence, the model is robust so we can obtain relatively accurate drag data quite quickly.

A drag coefficient value of 0.11 was achieved using CFD. This value meets our goal of having a drag coefficient lower than that of a submarine by incorporating dolphin-like features. The incorporation of the airfoil-like fin reduced the drag, and we achieved a drag coefficient between that of a typical submarine and a dolphin. Although this coefficient is more than ideal, we were skeptical of this result. By taking a 2D cross sectional area to be a reference area for the drag coefficient and then importing this into Ansys Fluent for further analysis, it was found that the drag coefficient was the same as before, so the result was reliable.

It was briefly mentioned in the presentation that a “3D drag calculation” was used to obtain the drag coefficient and we planned on instead using a “2D drag calculation” for better results. What was meant by this was that we imported the 3D shape into Ansys, then specified a reference area going through the middle of the housing shape to test the drag coefficient. Since the coefficient seemed low, we plan on instead making an appropriate 2D cross-sectional CAD rendition of the 3D CAD model and then importing the 2D rendition into Ansys to test drag on. We suspect that there may have been a mishap in choosing a specified reference area initially and this could have possibly contributed to the low drag coefficient.

For the pressure and velocity contour plots, we wanted to use a more accurate model to obtain our contours. Since the mesh was not the highest quality possible, we needed to obtain good data while also keeping the computing power reasonably constrained. An SST K-Omega model was used for pressure and velocity plots with water being the acting fluid material. This model was used because it provides much better flow data than SA while keeping computing power relatively low given the quality of the flow data. Although this model requires a fine mesh resolution near walls, we still used the model because the points of high interest, such as at the fin interface, still had a fine mesh resolution even though points of lower interest, such as the sides of the submarine, had a coarser mesh resolution.

Figure 5 below shows the obtained velocity contour plots, in meters per second, to help us better understand and visualize how our robot would move underwater and help us identify possible points of interest to improve upon in design such as the airfoil-submarine interface.

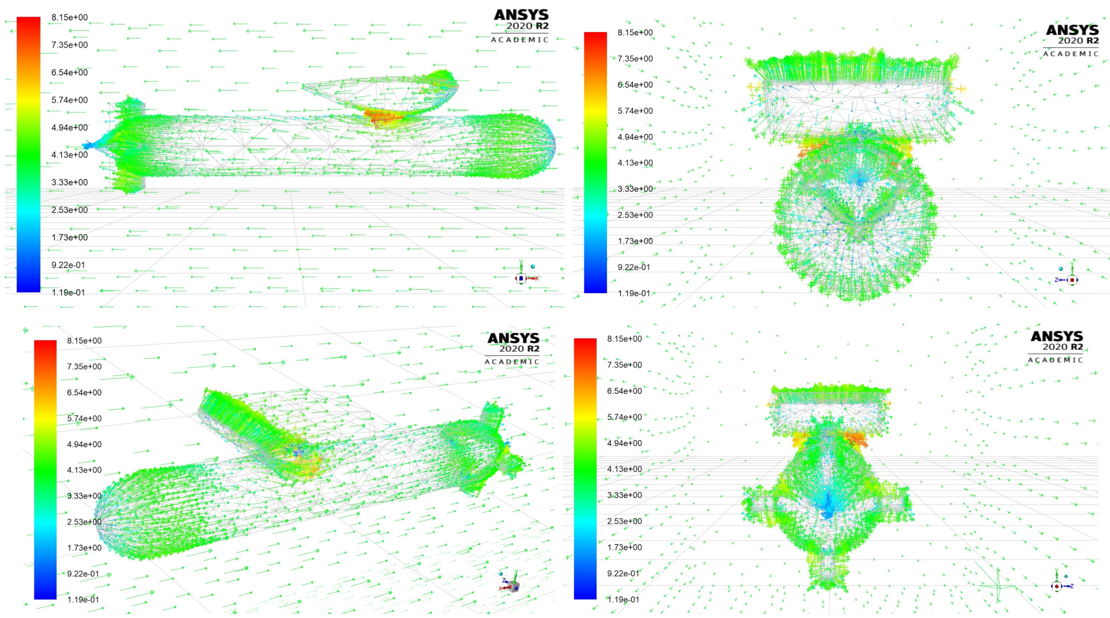


Figure 5. Velocity contour plots displayed at various angles.

Figure 6 on page 16 shows the obtained pressure deviation contour plots in units of Pascals to help us better understand points of interest such as the airfoil interface, the front of the airfoil, and the front tip of the submarine structure. We must make sure the aforementioned regions are made of materials that can withstand these kinds of pressures to satisfy the “durability” requirement.

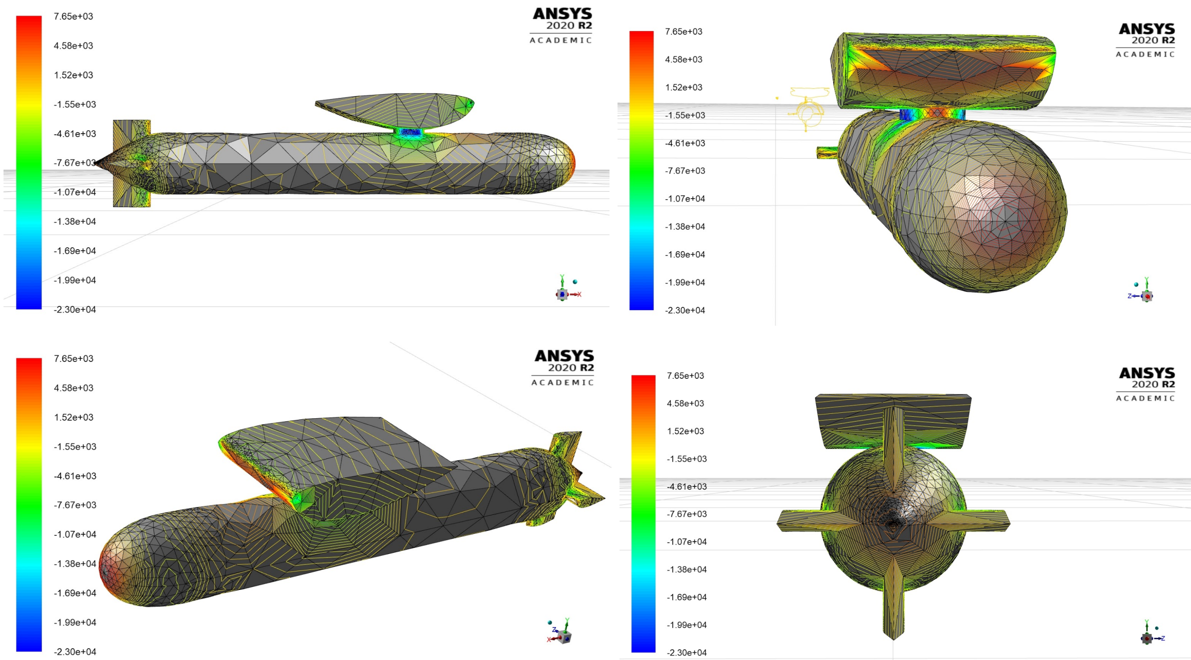


Figure 6. Pressure contour plots displayed at various angles.

Under the durable requirement, a specification of "Must be able to operate ≥ 3.5 hours with a standard equipment setup and at consistent power consumption" was specified. By studying the pressure and velocity contours and lowering the drag coefficient, we are able to ensure that the force required to propel the robot is reduced thus contributing to a lower power consumption per unit length travelled and ultimately a longer operating time to push us over the 3.5 hour minimum operating time. The high pressure zones identified by the pressure contours helped us satisfy the "waterproof" specification in that we can ensure the high pressure areas are either reinforced or made of materials that can withstand these pressures without collapsing. A complete calculation and engineering analysis of the pressure vessel design can be found on page 28 of the engineering analysis section under "Vessel Design Analysis".

Power Source

From our brainstorming discussion, we determined that the four best concepts for a power source were lithium ion batteries, lithium polymer batteries, hydrogen fuel cells, and an electrical cable tether. These four were the best concepts generated due to their widespread utilization as power sources and proven abilities in underwater robot applications. Research on the pros and cons of the concepts were conducted and are compiled in Table 5 on the following page.

Table 5. Concept Evaluation of Power Sources

Power Source Types	Description	Pros and Cons
Lithium Ion Battery	Rechargeable batteries commonly used in electronics and industry	+ High energy density (100-265 Wh/kg) + Widely used and research proven - Temperature sensitive - Dangerous if ruptured

Lithium Polymer Battery	Uses a polymer electrolyte instead of liquid ones which eliminated leakage	+ Efficient packaging - Less energy dense than standard Li-ion - More expensive - Short lifespan
Hydrogen Fuel Cells	Fuel cells that combine hydrogen and oxygen to generate electricity, heat, and water. A technology recently being used by the automotive industry	+ Only waste product is water - Complex system - Hydrogen fuel is expensive - Requires an on board O2 tank
Electrical Cable Tether	Traditional method for powering and operating ROVs. The cable is usually tethered to a boat with an on-board generator	+ Long operation time - Cost increases with length - Requires an external power source

From our research and after evaluating the different advantages and disadvantages of each power source we determined that a lithium ion battery was the best solution. It not only is the most widely used rechargeable battery type, which aids to our cost requirement, but is also very energy dense and research proven with AUVs and various robots alike. The energy density is proven later in our analysis portion of the report on page 32 under "Power Source Design Analysis".

Sensors

Following the sensor concept generation, our team was left with many possible sensor options and combinations. The first step we took in concept evaluation was to categorize sensors by which sensors can work best in combination with other sensors (a multiple sensor subsystem), and which sensors function primarily on their own. Examples of sensors that can work best in a multiple sensor subsystem are the Inertial Mass Unit (IMU) and the Doppler Velocity Log (DVL), which are often used in combination as a navigation/positioning system, as their combined application provides much greater functional benefit than either of the individual sensors. Our selection of sensors (from Table 2 above) that fall into the category of sensors that work best in a multiple sensor subsystem, along with some pros and cons of each, can be seen in Table 6 one page 15. The pros listed will be denoted by "+" and the cons will be denoted by "-".

Table 6. Concept evaluation of sensors that work best in a multiple sensor subsystem

Sensor Type	**Pros and Cons**
Inertial Mass Unit (IMU)	+ Measures angular rate and force, allowing determination of orientation and acceleration measurement + Relatively small device - Cannot measure velocity

Doppler Velocity Log (DVL)	+ Uses sonar to measure velocity relative to the sea floor - Cannot determine orientation of vehicle - Sonar capabilities are insufficient for mapping seafloor
Depth/Pressure Sensor	+ Measures the vehicle depth/pressures faced by vehicle + Useful for ensuring vessel is within safe depth/pressure ranges - Extra space and power consumption
Relative Position Sensor (Hull-relative or seafloor-relative navigation)	+ Provides a fairly precise location of vessel in relation to its deployment vessel/seafloor + Relatively cheap - May be redundant depending on the other sensors present
Global Positioning Sensor (GPS)	+ Provides a precise location of vessel over a vast area - Device only functions at surface, ineffective underwater - Inferior functionality when compared to a relative position sensor for this application
Moisture Sensor	+ Ability to detect breaches in vessel or damaging levels of moisture - Only effective if paired with some type of safety/protection system

After considering the pros and cons of these sensors, we determined that the IMU, DVL, depth/pressure sensor, relative position sensor, and moisture sensor would be best to include on the robot, and the GPS would not be a valuable addition. The IMU and DVL work well as a navigation/positioning system in combination, providing an orientation, acceleration, and velocity measurements to the robot controller. The depth/pressure sensor is a valuable addition as it can provide measurements of the robot's depth and ensure the vessel faces safe pressures. The relative position sensor was also determined to be a worthwhile addition to the chosen sensors, as the low cost and reasonable precision of the sensor can prove beneficial in applications such as recovery and ensuring the robot follows the intended route. We determined the GPS should not be included as it has poor underwater functionality, and any other remaining benefits would be made redundant by the relative position sensor that is already being included. The final sensor considered was the moisture sensor, which we determined would be included as it would be critical in any type of safety/protection system, and it is relatively low cost and takes up little space.

The sensors that our team categorized as functioning primarily on their own are Light Detection and Ranging (LiDAR) and Sonar, these being the sensors used to map the seafloor. In Table 7 below, descriptions of LiDAR and various types of Sonar, along with the benefits of each are provided. The pros listed will be denoted by "+" and the cons will be denoted by "-".

Table 7. Concept evaluation for seafloor mapping method.

Mapping Method	**Description**	**Pros and Cons**
Light Detection and Ranging (LiDAR)	Measures distance to the seafloor using a pulsed laser and sensor, the collected data is compiled to create a seafloor map	+ Functions well in shallow waters - Much of the emitted laser pulse is redacted and does not return to the sensor in deeper waters - Relatively expensive for this application
Side-Scan Sonar	Echo sounders/sensor arrays are mounted to the sides of a vessel, allowing mapping of a large coverage area	+ Acoustic waves travel well through water + Relatively large coverage area - Tradeoff between resolution and vessel speed along with coverage area
Multibeam Sonar	A multi-element array of echo sounders is used to map the seafloor; this array is primarily downward facing	+ Acoustic waves travel well through water + High resolution depth data - Poor coverage area compared to side-scan systems
Synthetic Aperture Sonar (SAS)	Side-scan sonar in combination with integrated signal processing allows for improved resolution over range by combining information from multiple acoustic pings [11]	+ High resolution over large coverage area - Greater computing power required and greater power consumption - More expensive than options without integrated signal processing
Interferometric Synthetic Aperture Sonar (InSAS)	Synthetic Aperture Sonar in combination with interferometric processing uses multiple pings at varying frequencies to further improve resolution and coverage rate [11]	+ Best resolution over large coverage areas + Improved area coverage rate - Most expensive sonar sub-type - Greatest power consumption and computing power required

With the pros and cons of different seafloor mapping methods considered, we felt we could easily eliminate LiDAR and multibeam sonar mapping methods for this application. LiDAR's use of laser pulses is not ideal for underwater application where deeper waters will be the most common use environment due to the light refraction that occurs, weakening the signal returning to the sensors. This will have a significant negative impact on the resolution of the mapping we are able to achieve, preventing LiDAR from being a viable option. We felt we could also rule out multibeam sonar due to its small coverage area compared to all side-scan sonar variations, while its resolution is matched or exceeded by SAS or InSAS. Because multibeam sonar is outperformed by side-scan sonar variations such as SAS and InSAS and it has a smaller coverage area than desired, we were able to rule it out from being the selected seafloor mapping method. This leaves side-scan sonar and its SAS and InSAS variations as candidate concepts for the seafloor mapping sensor. Traditional side-scan sonar is the cheapest option but it is outperformed by the SAS and InSAS sonar versions. SAS sonar differs from traditional side-scan sonar as traditional side-scan sonar will send out a single "ping" and must wait until the acoustic wave returns before sending another ping. SAS is able to perform constant pinging without the need to wait for the return due to advanced signal processing, allowing for greater detail than traditional side-scan sonar through much more data of seafloor depth being taken and processed. Exact specification differences can vary based on sonar model and pinging frequency. InSAS follows the same trend of constant pinging, but is able to send pings of differing frequencies. Upon return, the signal processing is able to determine the constructive or destructive interaction of the waves based on return frequency, and then can make the most accurate measurement of the seafloor of any sonar type through use of interferometry. Though the goal is to obtain the highest quality seafloor maps possible, our design choices are also constrained by budget. The SAS and InSAS sonar are the best performing options, the cost of this technology is beyond what our budget will allow, thus we select side-scan sonar as the type of sonar system that will be used on the robot.

Kinematic Systems

According to the research, the sonar detection requires the sensor moving parallel to the seafloor smoothly. Therefore smooth motion, continuous motion, becomes critical to evaluate the system. Hence we are able to eliminate those concepts to three concepts that could provide relatively smooth movement. A Pugh chart is created in Table 8 to evaluate concepts. The design criteria is weighted according to how large it would impact the body motion and sonar detection. The concept "Propellers in x,y and z axis" would be the base case, as it would be easiest to construct and implement. The result is shown in Table 8 below.

Table 8. Pugh chart for weighing different possible options for the kinematic system.

Criteria	Weight	Propellers in x,y,and z axis	One strong propeller with a rotational junction	Reaction wheels with discrete motion
Continuous motion	10	0	0	0

Cost of Actuators	5	0	1	0
Manufacturability	2	0	-1	-1
Complexity of Control	10	0	-1	-1
Ave. Speed	3	0	1	0
Size and Weight	10	0	1	-1
Total		0	6	-22

As shown in Table 8 displays, "One strong propeller with a rotational junction" is slightly better than the base case. Hence, it was decided that two concepts with the propeller would be best fit for our project. The further exploration of these two concepts is required due to the uncertainty on rotational junction control and structure.

Protections

Because these robots are expensive, roughly 70,000 dollars on average, we decided we needed an emergency protection device that prevents the robot from sinking to the bottom of the ocean if the seals fail and the robot fills with water. This also distinguishes our robot from what is already in existence at Bluefin Robotics for example. After discussing this concept system with our expert Professor Ram Vasudaven, he informed us that sensors themselves are relatively cheap, it is the housings and robot itself that are expensive. We used the brainstorming rules to generate many concepts to save the robot, the three methods shown in Table 9 below were subsequently developed.

Table 9. Concept evaluation for different protection methods against water leakage into the robot.

Protection method	**Description**	**Pros/ Cons**
Airbag attachment	An airbag similar to what is used for crash safety in a car, connected to a pressure sensor or weight sensor. It goes off when pressure or weight is too high	+ All energy used for the airbag is internal, does not require any power input from the robot + Most expensive option - Will require GPS for retrieval - Airbag could get punctured by something when it inflates
Tethered Robot	Attachment of the robot to a boat by a tether	+ Will not require any sensors or gps + Cheapest option - Is weather dependant

		because it requires a boat - Tether could get snagged or break
Emergency motor	An emergency motor that turns on when the pressure or weight is too high. The robot is sent to the surface and kept there by the motor until the team retrieves it.	+ Could give one of our existing motors the potential to do this - Will require GPS for retrieval - Needs a large time interval so that the team has enough time to retrieve it - Motor would need to be protected from overheating

After weighing the pros and cons of each of our robot housing protection concepts, we decided to use an underwater airbag. The underwater airbag is the most expensive of the three concepts, but the benefits of being able to operate independently of a boat, and the airbag would be easier to retrieve than the emergency motor. There are glaring problems with the emergency motor concept because it would require a large power requirement to overcome gravity to reach and stay at the surface. The airbag design would also require a position sensor to allow the team to find the robot once it reached the surface.

Unfortunately, due to the challenges and time constraints from the project, we were unable to continue pursuing this aspect of the project and did not design an airbag. However, we do not think that the cost of an airbag system would increase our overall design cost to over the 70,000 dollars requirement, as our current overall design cost is under 22,000 dollars.

Final Design Solution

After detailed consideration of the final concepts for the subsystems were combined to develop a unique design to meet the requirements.

Vessel Design

The vessel shell design incorporates a common cylindrical submarine type silhouette with an attached airfoil and fins to improve the vessel's ability to glide through water with stability. This vessel shell will serve as the housing for all of the robot's subsystems and will face the underwater pressures as the robot's exterior structure. A SolidWorks model of the exterior shell is shown below in Figure 7.

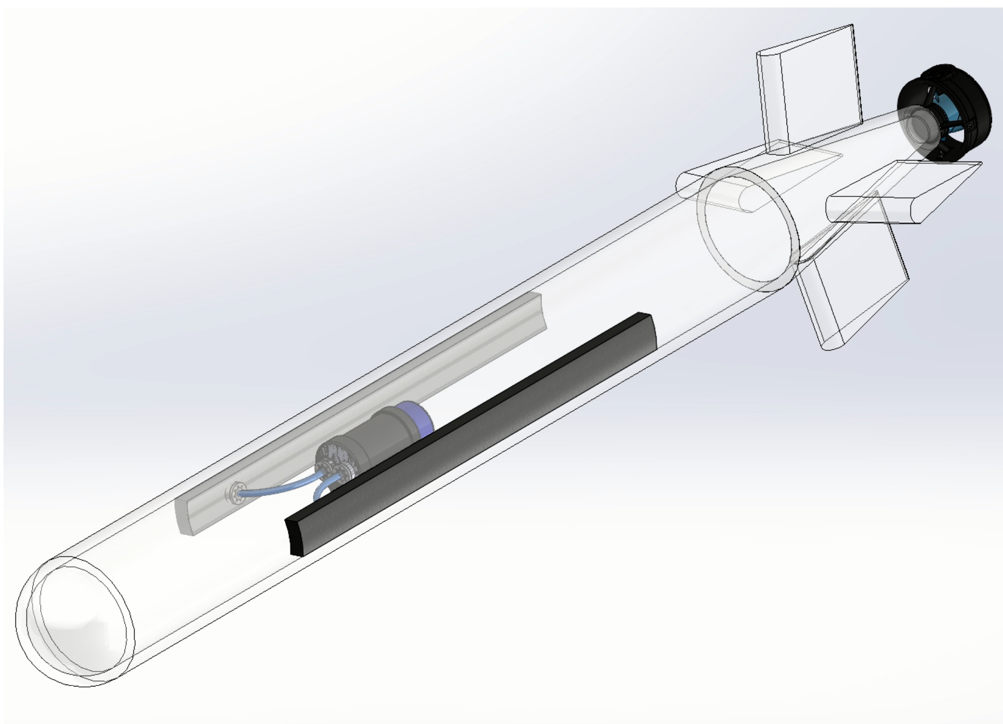


Figure 7: SolidWorks model of the current robot exterior shell design

The dimensions of the vessel shell are listed below in Table 10 below.

Table 10. Dimensioning of vessel shell

Dimension	**Measurement**
Axial Length (without propellor)	2.5 meters
Outer Diameter	0.25 meters
Inner Diameter	0.21 meters

Vessel Material
For the material of the vessel, our team considered options of materials that have been implemented in an underwater vehicle in industry, such as various aluminum alloys, titanium alloys, steels, and plastics. After some consideration and research of existing market solutions, we decided that a polycarbonate material with an exterior protective coating would be used. Use of a polycarbonate structural shell with a protective exterior coating is fairly common in currently existing AUV's, and has some distinct benefits over the use of metals. Some of these benefits of polycarbonate include being lighter weight, cheaper, and easily manufactured (injection molding, extrusion, thermoforming), all while being relatively abundantly available. The benefit of a lighter weight material is the reduction of the full system weight, which will require less thrust force to meet the robot's specification of moving at 0.5 knots, making this specification easier to fulfill. Polycarbonate is a material with good impact resistance, but is somewhat susceptible to scratches, which warrants the use of a protective exterior coating.

Polycarbonate also has other material properties that are beneficial for the underwater vehicle use case, such as the availability of filler materials (such as glass fiber) which can help to improve the mechanical properties of the polycarbonate. Polycarbonate also works well to fulfill the durability requirements, and specifically the temperature range specification of operation at -2°C, as polycarbonate can maintain its mechanical properties well within this temperature range and maintains rigidity between -20°C and 140°C. Basic polycarbonate has a tensile yield strength of ~9500 PSI but this can be modified with the addition of fillers or alloying the polycarbonate [13].

Center of Mass Controller Design
Some underwater robots can dive to a specified depth and resurface. They can also hold their depth underwater and move around. This is known as snorkeling. The mechanism to assist snorkeling can be broken down into three subassemblies: the mass subassembly, the motor bracket subassembly, and the slider base subassembly. The mass subassembly is responsible for attaching the mass on the belt and the track. The motor bracket assembly is used to hold the motor and protect the motor from moisture. The slide base assembly is used to set the track, belt, pulley and motor bracket. Figure 8 on the next page shows the dimensionless model of the device with all subassemblies included.

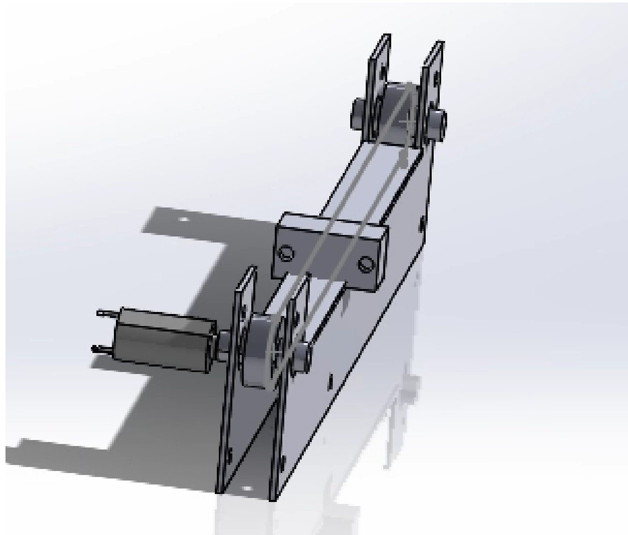


Figure 8. This is the preliminary figure for this device. Some components cannot be shown detailly in this are the motor bracket, the specific motor will be used in this, and the track under the mass.

The Mass Assembly
The mass itself has three components. The belt will be clasped by two small pieces of the mass with fasteners. The mass of this piece is not yet determined and will be calculated from the solidworks model. The CAD model is shown in Figure 9.

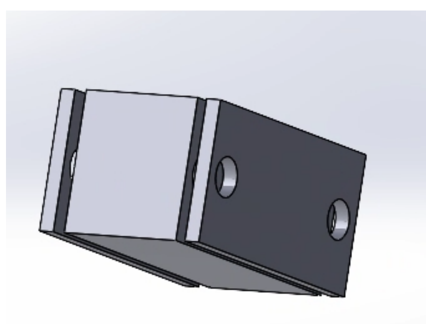


Figure 9. Image showing the mass components and how it will clasp the belt using fasteners

Motor Bracket Assembly
The motor bracket subassembly is used to stabilize the motor and the shaft coincides with the pulley in the slider base. Also, the motor will have a second secure with a motor shaft pin to insure the motor is connected to the pulley rigidly. The motor bracket is attached to the slider base and the motor using fasteners. The motor itself will not be allowed to be moved. Additionally, to avoid the possibility that the rising water shorted out the electrical system (motor), the motor will be oil-sealed via the O ring. This part is not completed yet since we haven't decided the motor and mass on the track yet and the motor is required to drive the mass.

Base Assembly

The purpose of this subassembly is to provide support to the motor bracket and track and the pulleys with the belt. This base includes two pieces of acrylic plates with holes or similar 3D printing components. Small holes will fit with fasteners and two large holes will fit with the shafts and the pulleys. One of the pulleys will attach to the motor using the motor pin. Thus, the motor's rotational motion will drive the pulley, the belt, and the mass. To assure the mass's movement direction is longitudinal, the mass is on the track also the track to avoid the vibration of the belt. The model is shown below.

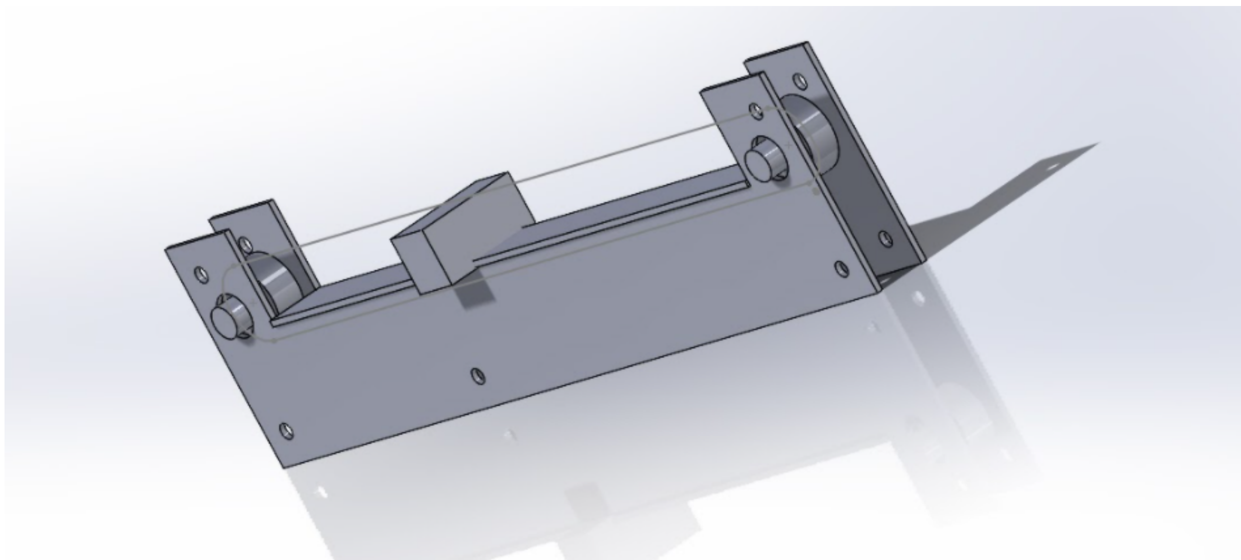


Figure 10. Base assembly. The assembly contains two pulleys with a belt, one mass with a track, and two pieces of plates.

The center of mass control design works by shifting the center of gravity of the underwater robot lengthwise. The track is positioned within the robot so that the mass can move either towards the front end (nose) or towards the rear end (propellor). This ultimately shifts and manipulates the center or mass of the overall design forwards and backwards. If the robot is to dive down, we can shift the center of mass towards the nose. To raise the robot, the mass is shifted backwards. The mass is connected to a track to keep it mounted but still slidable, and is moved back and forth by being attached to a belt and pulley system. The entire system is controlled with a motor and a motor controller. The motor is attached to a single pulley which when rotated clockwise or counterclockwise, moves the belt, and thus the mass, forwards and backwards.

Power Source Design

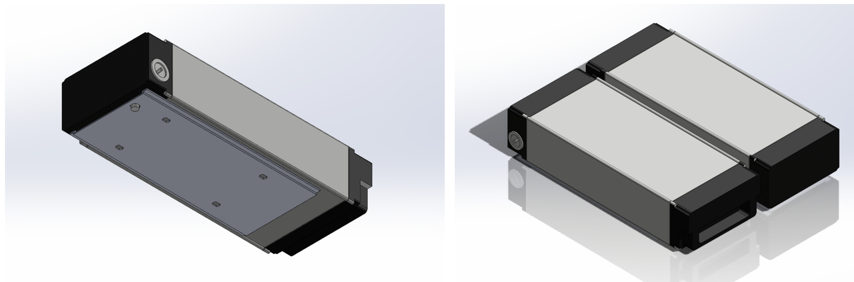


Figure 11. Battery design showing mounting bracket and lock and in parallel configuration

For the power source design we decided to use a 48 volt 20 amps battery pack designed for electric bicycles. This battery is a pre-existing solution that one of our team members have worked with before for robotics. The benefit of this is that it is cheap, readily available, and has validated results. The battery costs just under $200 and weighs 8.5 kg and comes with an integrated handle to help with portability. It is designed with a locking mechanism which not only secures it to an included mounting bracket but also powers the battery on and off. The locking mechanism and bracket allow for quick battery changes and can be seen in Figure 11 above. Although each battery has a slow recharge time of about 8 hours from empty, the low cost and easy battery swap procedure helps justify its use and as a viable power source. The verification of using this battery is further detailed on page 27 in the engineering analysis section of this report.

Waterproof Design

In order to protect the electronics of our robot from becoming damaged we need to construct waterproof housings that will remain waterproof at 30 meters below the surface for 3.5 hours. If there is a purchasable housing for a particular component, we will purchase this, and manufacture whatever housings remain unaccounted for.

At component interfaces where water must be sealed out, we plan to use 3M Marine Grade Silicone for seals and rubber washers and gaskets to waterproof at fastener locations. Neoprene rubber is the material we chose for the gaskets, as they are rated to a pressure of 150 PSI, which is greater than the pressure present at the robot's specified operating depth within the durability requirement. Furthermore, we plan to seal all static mating surfaces with silicone, and all dynamic mating surfaces with gaskets and gasket sealer so that they may be disassembled at a later point.

Engineering Analysis

Mass Analysis

To ensure the critical equilibrium under the water, the mass will need to be analyzed at the first.don't think we need this part. In this analysis, one spread-sheet, fig[], is created to include all the materials and components the robot has with their mass. The mass value will be the average mass for each component. This analysis does not include the mass of fasters. All details are included in the BOM. The total mass of the robot m is used to determine the volume of the robot V_{vessel} using the following equation.

$$V_{vessel} = \frac{m}{\rho}$$

Where the ρ is the density of seawater, $1027\frac{kg}{m^3}$.

After the analysis, the total mass of the robot is 103.47 kg and the volume of the vessel is around 0.103 m^3 . The dimension in the final solution is determined from this calculated volume, 2.5 m X 0.12 m X 0.02 m.

Moreover, since the AUV needs to move parallel to the seafloor during the seafloor mapping. The AUV is expected to have balance on the head and tail. This could be achieved by placing different components in different locations. The balance could be examined by the following equation.

$$\Sigma m_h r_h = \Sigma m_t r_t$$

Vessel Design Analysis

To verify the integrity of the vessel shell in the use environment, we used basic hand calculations and ANSYS Static Structural Finite Element Analysis (FEA). Using the dimensions of the vessel listed above, we performed a basic calculation for the hoop stress that the vessel would be subjected to in order to determine if the vessel design would be robust enough to withstand the estimated pressure of the underwater environment. For simplicity, we assumed the properties of a cylindrical thin walled pressure vessel for our shell. Using equation 1 and the estimated pressures at the specified operating depth [14] we estimated the hoop stress, where σ_{hoop} , P, r, and t represent hoop stress, pressure, radius, and wall thickness respectively.

$$\sigma_{hoop} = (P_{external} - P_{internal}) * r/t \qquad (1)[18]$$

$$\sigma_{hoop} = (405.3\ kPa - 101.3\ kPa) * 0.12\ m/\ 0.02\ m$$

$$\sigma_{hoop} = 1824\ kPa$$

The resulting hoop stress is 1824 kPa, and with the compressive yield strength of molded polycarbonate documented to be 76.0 - 86.2 MPa [13] we can assume that our vessel will likely not fail due to stresses resulting from external pressures. The compressive yield strength was referenced due to the external pressure on the vessel. We realize this results in a larger safety factor than necessary, but this thickness was chosen in order to help balance the weight and it's buoyant force, which is necessary for proper operation.

Following these hand calculations we simulated our design with these conditions using ANSYS Static Structural FEA. The material properties of molded polycarbonate were used for the vessel [13], and the vessel was meshed using a sweep method, with a symmetry feature implemented in order to save computing power. An element size of 0.005 m was used in order to guarantee at least 3 elements along the thickness of the vessel. Figure 12 below shows the meshed body with the symmetry feature applied.

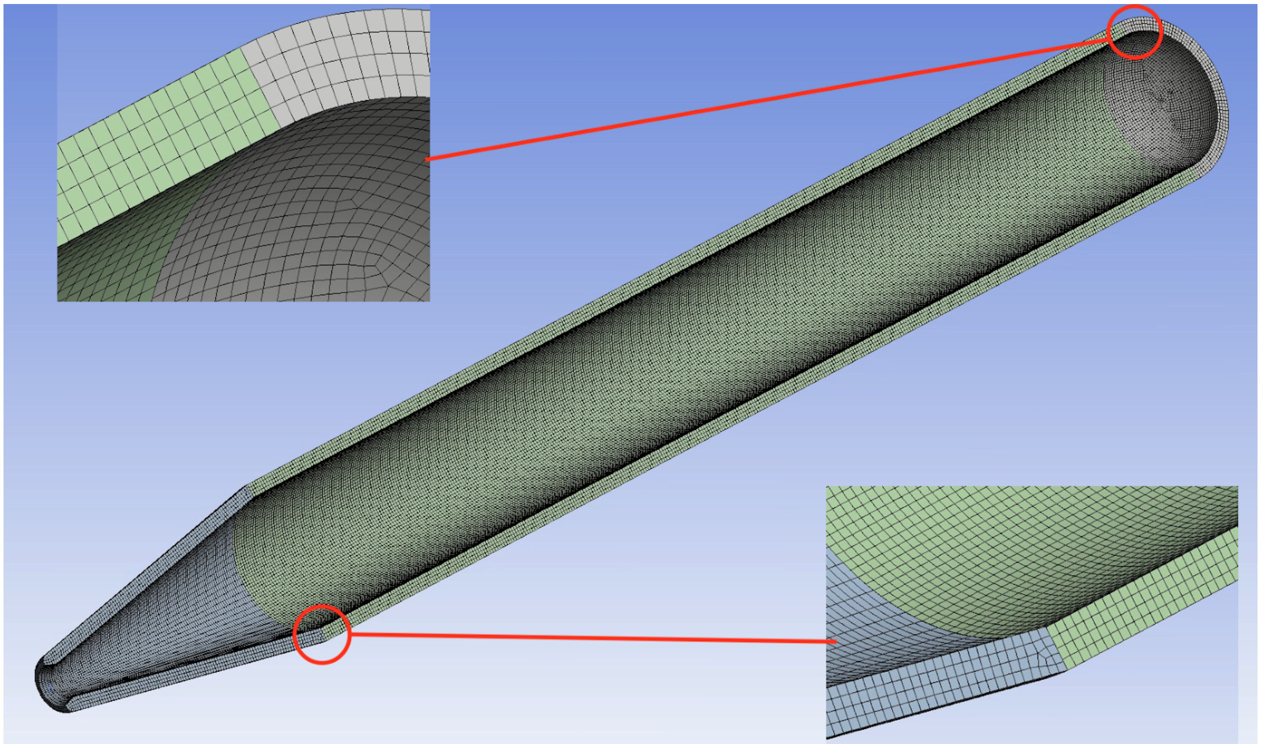


Figure 12. Meshed vessel shell with zoomed views

For the boundary conditions, pressures were applied to the interior and exterior of the vessel, with the exterior pressure set to 405.3 kPa and the internal pressure set to 101.3 kPa. A deformable remote displacement support set to zero displacement and rotation in all directions was applied to an inner surface of the tail. In the full assembly this area would be further reinforced by elements of the propellor subsystem, so we felt it was the best point to constrain the vessel at, this support can be seen in Figure 13 on the following page.

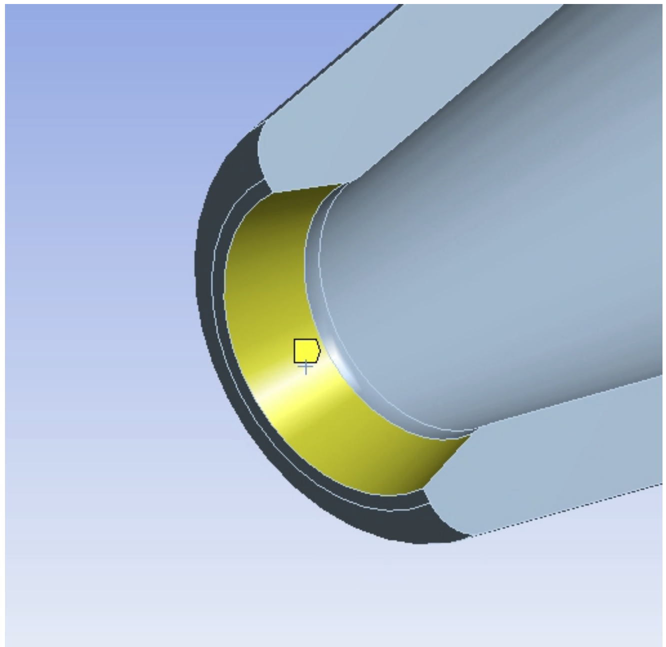


Figure 13. Constraining support surface of vessel

With these conditions applied, the simulation was solved for equivalent stress and produced the results shown in Figure 14 below.

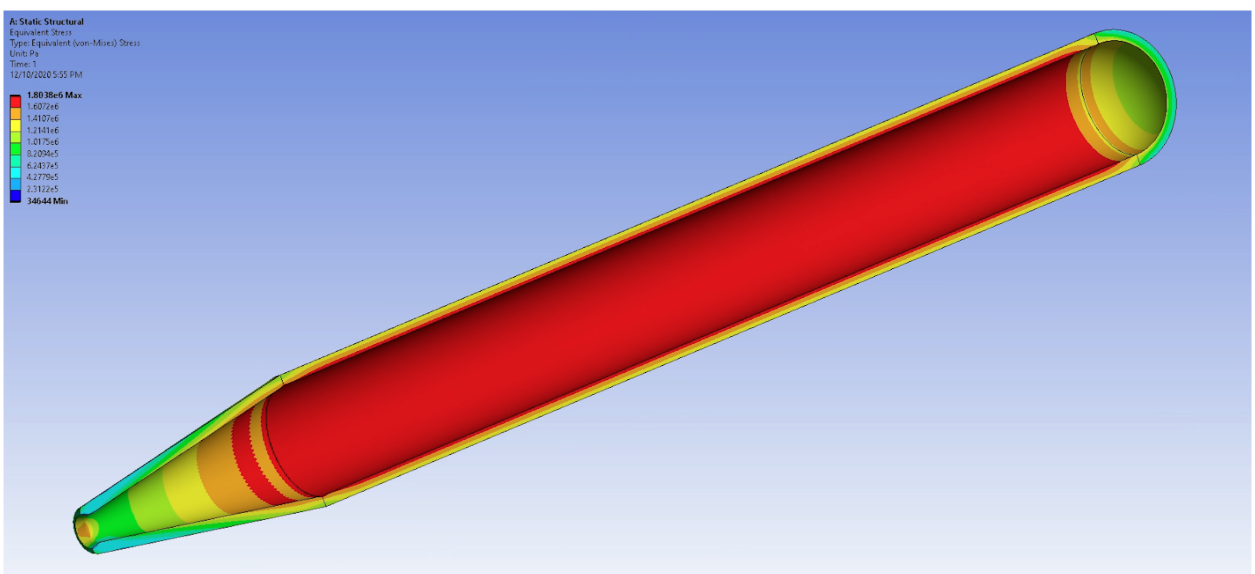


Figure 14. Pressure vessel simulation results

The area shown in red represents the area where the maximum stress is present on the body, and this value was listed as 1804 kPa by the solver. This value is similar to the hand calculated stress of 1824 kPa, which suggests that the solver provided maximum stress value can be trusted. Like the previous stress result, the value of 1804 kPa is far less than the compressive yield strength of molded polycarbonate which is 76.0 - 86.2 MPa [13]. This suggests that our vessel will maintain its integrity against the pressure below water. All results shown are assumed to be symmetrical for the hidden section of the vessel.

Simulation by this method does have limitations, and can become very complicated with the more specific that the boundary conditions applied are. ANSYS can also present faulty or incorrect stresses in the body depending on the quality of the generated mesh elements, which can skew results drastically. Though this simulation greatly simplifies the operating conditions of the vehicle, the maximum stresses are present in the areas where they are expected, and the solved results are very similar to the hand calculated stress value. These are signs suggesting that the simulation is likely working as intended, and for the purpose of determining if our vessel will maintain integrity at the operating pressures, this simulation supports the conclusion that our vessel is well enough reinforced even considering the simulation's limitations. The large safety factor of about 42 times for the conservative compressive yield strength also supports the conclusion that our vessel is well enough reinforced.

Kinematic Design Analysis

Center of Mass Controller Analysis

The center of mass controller is used to tilt the robot, in other words, there will be rotational movement respected to the equilibrium center of mass. The ultimate goal is to have the angle displacement. This analysis is to determine the angular displacement. To better visualize the mechanism, a free body diagram is used to illustrate the system shown below.

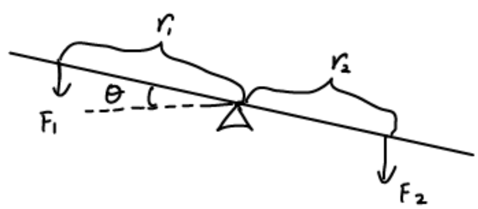


Figure 15. Free body diagram of the robot in longitudinal direction.

The angular displacement $\Delta\theta(t)$ is the double integral of the angular acceleration. Therefore the total torque τ_{net} ,the angular acceleration α ,the rotational inertia I , and the angular velocity $\omega(t)$ were calculated with equations 2-6:

$$\tau_{net} = F_1 r_1 sin(\theta) - F_2 r_2 sin(\theta) \quad (2)[15]$$

$$\alpha = \frac{\tau_{net}}{I} \quad (3)[15]$$

$$I = mr^2 \quad (4)[15]$$

$$\omega(t) = \int_0^t \alpha + \alpha_0 \, dt \quad (5)[15]$$

$$\Delta\theta(t) = \int_0^t \omega + \omega_0 dt \quad (6)[15]$$

Where m is the mass on the slider, r is the displacement from origin or pivot. With these equations, the state space form of the system could be formed.

Propellor Analysis

From our specifications, the AUV is required to move above 0.5 knots under the water. To achieve this, the propeller needs to supply enough thrust. The equation below is used to calculate the required thrust.

$$Thrust = AV^2 \frac{\rho}{2} Cd \quad (6)[15]$$

where ρ is the density of salt water (~1025 kg/m^3), Cd is the drag coefficient calculated from shell analysis(0.11) A = vessel's frontal area(0.098175m^2), V = moving speed(≥0.257m/s). Once we have finalized the frontal area of the vessel,the required thrust can be calculated and used to select the propellor. The required thrust for the robot to meet the velocity specification is 0.366 N.

Power Source Design Analysis

From our specifications, the robot needs to operate for a minimum of 3.5 hours with all components powered and running. In order to achieve this, the total watt hours of all the electrical components of the robot needs to be less than or equal to the total watt hours of the power source, which in this case is the battery design. Table 11 below shows the power usage of each electrical component and its calculated watt hours.

Table 11. Watt Hour Calculation

Component	**Power Usage (W)**	**Total Watt Hours**
Sonar	5	17.5
Propellor Motor	500	1750
Center of Mass Motor	20	70
Extraneous Computing	20 (Estimated)	70
		1907.5 total watt hours

The power usage of the components were found and the total watt hours were calculated by multiplying the power usage by our 3.5 hour design specification. The sonar power usage was determined by researching different underwater sonars used in our specific application. For both the propellor and center of mass motors we decided on a powerful 500W motor for the propellor and a small but standard 20W motor for the center of mass motor. For the extraneous computing that would be used to connect and control the different electrical components of the AUV we estimated 20W of power usage, which is similar to a small laptop. All the components watt hours were added together to get a watt hour target of 1907.5 Wh for the battery design.

To calculate the power availability of a battery pack you multiply its voltage by its amperage to determine the number of watt hours. This calculation is shown in equation 7 below.

$$\text{Volts} \times \text{Amps} = \text{Watt hours} \qquad (7)[16]$$

From our chosen battery with 48 volts and 20 amps a single battery pack yields 960 watt hours. This does not meet our required 1907.5 Wh number so we decided to use two battery packs wired in parallel which adds the two batteries 20 amp rating into 40 amps. When multiplied by 48 volts this yields 1920 watt hours which meets our specifications.

Waterproof Analysis

We calculated that the robot needed to remain waterproof at a distance of 30 meters below the surface, which meant our waterproof housings have to withstand pressures of 150 psi. We chose to use 70 shore A durometer neoprene rubber as our gasket material. Through research we determined the thickness of the gaskets to be 1/8th inch thick and compressed to 45% of its original thickness [17]. The 70 shore A neoprene is a relatively soft rubber similar to a shoe sole, it was chosen because it requires less compressive force to remain waterproof. We will use the neoprene gaskets on all dynamic mating surfaces with a gasket sealer to adhere the gasket to the surface. A quarter inch wide groove will need to be machined to a depth of a quarter inch into the cross sections of the two mating surfaces to allow an o-ring gasket to be inserted. The dynamic surfaces will have to be compressed with 70 lbs of force to allow the surface to be water tight at 30 meters. There will be a door that opens to allow for maintenance and data collection, this door will have to be fastened with a torque wrench to 70 lbs. We may need to add structural brackets with nuts and bolts to not damage the polycarbonate. Any exposed bolts or fasteners will have to be siliconed to prevent leaking. For static mating surfaces if the polycarbonate panels need to be fastened together we will use acrylic glue because it is recommended to bond well with polycarbonate and we will silicone these seals for added protection.

Full System Embodiment

The full system embodiment of the AUV with the vessel design, power source design and center of mass controller design is shown in Figure 16 below.

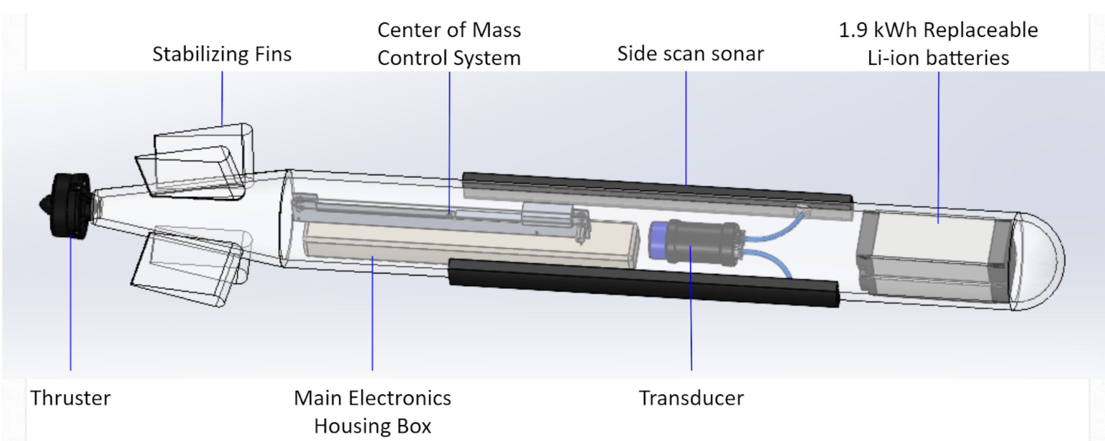


Figure 16. Model of complete AUV with full system embodiment of current systems

All the systems are housed within the polycarbonate vessel design which is transparent in Figure 16 to help with visualizing the full system embodiment. The main thruster, which is BlueRobotics T200 thruster, can be seen at the rear of the robot with the idea that it is mounted on a controllable swivel to help with maneuverability. The four stabilizing fins of the shell design are also in the model and also made from polycarbonate. The main electronics housing box is shown which houses the controls and electronic wiring necessary for the battery to power all electronics, including the rear thruster, center of mass controller and the sonar and sonar data storage device and computing. The idea is for all sensitive electronic components to be housed within this box to protect it from moisture and in the catastrophic event that the shell is breached, we can still hopefully recover the electronic equipment and sonar data. The side scan sonar can be seen with the transducer mounted inside the shell and the sonars mounted on the exterior and on the sides as the name suggests and as it normally operates. The battery pack can be seen near the nose end of the AUV shell design. As a whole, our AUV system design works together by having a complete shell housing, sonar system, battery pack design, and center of mass controller and thruster necessary to meet all of our requirements as shown in the "Verification" portion of this report on page 38.

Our team understands that this current full system embodiment model is missing key features and will require further engineering analysis. Key features that are missing include the electronics necessary to waterproofing gaskets and the location of any removable panels or hatches to demonstrate how components can be taken out and in for manufacturability and maintenance.

Bill of Materials

Figure 17 below shows the preliminary Bill of Materials that our team developed over the course of our solution development phase.

ME450 Team 6: Bill of Materials							
Part No.	Part Title	Dimensions	Weight of Purchased Material (kg)	Supplier	Qty	Price	Source Link
Sonars/Sensors							
1	SOS Leak Sensor	24.5 mm x 13.0 mm x 9.5 mm	0.005 kg	BlueRobotics	1	$29/ea	https://bluerobotics.com/store/sensors-sonars-cameras/leak-sensor/sos-leak-sensor/
2	AquaPix® MINSAS	Receiver: 53.0 cm x 3.0 cm x 7.0 cm, Electronics: 47 cm x 17 cm	26.2 kg	Kraken Robotics	2	Waiting on Quote ($10,000 estimate)	http://krakenrobotics.com/wp-content/uploads/2017/07/Kraken-AquaPix-Minsas-Brochure-17.09.15-low-res.pdf

		dia					
3	Inertial Navigation Systems	36.4mm x 94.1mm x 58.6mm	0.150 kg	Yost	1	$440.00	https://yostlabs.com/3-space-sensors/
Power Sources/Motors							
4	20V Thruster	Length: 113 mm, Diameter: 100 mm	6.7 kg	BlueRobotics	1	$206/ea	https://bluerobotics.com/store/thrusters/t100-t200-thrusters/t200-thruster/
5	12V DC motor 0.2 A	L:46.6mm D:30mm	0.151 kg	Transmec	1	$29.30	https://www.transmotec.com/product-category/dc-motors/
6	48V, 1000W, 20Ah Lithium Ion Electric Battery	360 mm x 150 mm x 80 mm	8.5 kg	Alibaba	2	$185/ea ($370 total)	https://www.alibaba.com/product-detail/Rear-Rack-48V-1000W-Electric-Bike_60254743506.html?spm=a2700.7724857.normalList.75.48335f78iGA5Vo
Manufacturing Materials							
7	Clear Polycarbonate Sheet AM	72 in x 48 in x 0.5 in	32 kg	ePlastics	1	$511.94	https://www.eplastics.com/LEXAN-CLR-0-500AM48X72
8	Polycarbonate Quote	Vessel Dimensions: 2.8m x 0.5m x 0.5m	60 kg (estimate)	Plastic Fab	1	Waiting on Quote ($10,000 estimate)	https://plasticfabinc.com/?gclid=CjwKCAiAzNj9BRBDEiwAPsL0d24ZjJPKkBT-lCMwl9IBfX_Nnk_uw8_zp5MRiF_9Cl_rO95WJH-V2RoClogQAvD_BwE
9	3M Marine Grade Silicone Sealant	Size: 3 oz	0.085 kg	3M	3	$13.07/ea ($39.21 total)	https://www.3m.com/3M/en_US/company-us/all-3m-products/~/3M-Marine-Grade-Silicone-Sealant/?N=5002385+3293194251&rt=rud
10	Acrylic Extruded Clear Sheet	0.08in x 24in x 48 in	1.8 kg	Acme plastic	1	$21.20	https://www.acmeplastics.com/acrylic-sheets/acrylic-extruded-clear-sheet
11	Boat Sliding Door Black Upper Track	29in x 1in x 1.125in	5 kg (estimate)	Boatoutfitters	1	$36.20	https://www.boatoutfitters.com/boat-sliding-door-black-upper-track?gclid=CjwKCAiA8Jf-BRB-EiwAWDtEGkZND6t3mT-7sM34GZouQX6aowgeLqVMELQXc

							KnqXHlAub9HALWNMRoCux4QAvD_BwE#203=412
12	1TB memory	4.60 x 3.15 x 0.58 inches	190 g	Seagate	1	$47.99	https://www.amazon.com/Seagate-Portable-External-Hard-Drive/dp/B07CRG7BBH
13	Mass block	7.5cm x 7.5 cm x 7.5 cm	3.556 kg	Alro Steel	1	$17.00	https://www.alro.com/divsteel/metals.aspx
				Total (Estimate)		$21,730.84	

Figure 17. Preliminary Bill of Materials developed and updated by our team during the solution development phase.

Figure 17 shows the Bill of Materials that includes all potential materials, parts, and components that we have considered at any point during the solution development process. We listed the materials that we have considered sourcing as well as the information about its sources and characteristics (e.g. dimensions, weight) to help us with determining the weight and pricing of our robot and specific part designs. The total value of our underwater robot design is estimated to be $21,730.84. Although we do not have complete list of materials and parts to create a completely functional AUV like having sensors, motor controllers, and other electronic components, we do believe that

Risk Assessment

For our proposed AUV design, we conducted an early-design FMEA (Failure Mode and Effects Analysis) as a formalized risk assessment. The summary of this risk assessment can be found in table 12 below.

Table 12. Early-design FMEA for proposed AUV design

Part	Potential Failure Mode	Potential Failure Effects	Severity (1-10)	Potential Causes	Prevention Control
Shell design	Pressure break	Catastrophic; loss of entire AUV	10	Poor manufacturing; incorrect analysis; fatigue from multiple uses	Quality control; increased safety factor for thickness of shell design; safety checks in between uses
Waterproofing	Water leakage/ ingress into robot housing	From minor water damage to complete	8	Poor manufacturing; incorrect analysis	Quality control; increased safety factor for gasket

		sinking of robot			thickness
Center of Mass Controller	Motor or belt breaks/slips	Unable to control robot balance and can lose robot entirely	6	Fatigue from multiple uses, pulley design for belt	Safety checks in between uses; pulley design with increased friction/better mating
Sonar	Sonar breaks and fails to produce image	Waste of data/ time and need to replace sonar	2	Part defect; fatigue from multiple uses	Safety checks in between uses
Battery Pack	Battery dies	Unable to retrieve robot in ocean	7	Low state of charge; efficiency drops from multiple uses	Safety checks in between uses

Action Recommended for High Risk Design Aspects

From our FMEA, we determined that the parts with the most severe failure effects are the shell and the waterproofing designs. For both of these parts, if there was a large breach of water into the robot, it could cause the entire vessel to sink or be destroyed. The waterproofing design is less severe as a small leakage of water could result in a range of large water damage to even no damage at all, whereas a break in the shell design would more likely result in a large breach of water and catastrophic damage. For both these parts, poor manufacturing and possible incorrect analysis could be contributors to these failures. As prevention to this, we can choose to increase the safety factor of our designs and increase both the shell and gasket thickness. We can also ensure that there is some form of quality control process when these parts are manufactured, whether it be a visual inspection or a engineering test.

Although the effects of failure are most severe, the likelihood of the shell and waterproof designs failing is not the highest. After much thought we view the center of mass slider part to have the highest likelihood of failure because it has two points of failure: the motor and the belt/pulley interaction. The motor used could fail while the robot is underwater, and could even cause the robot to sink from being too nose-heavy. The belt can also slip between the pulleys, which ruins the controlling accuracy of the system. To prevent these failures, the belt and pulley system can be upgraded by either including grooves into the pulleys and using a ribbed belt or even using a chain and sprocket system to help increase the friction and minimize/eliminate belt slip altogether. The motor and system can be checked in between each use and can be replaced after a certain amount of hours according to the manufacturer specifications to ensure it does not fail while the robot is in use underwater.

From our FMEA, we also found that a common potential effect from various failures is the sinking or complete loss of the robot. Therefore, to mitigate this, we have discussed using an underwater airbag to help save the robot and bring it back to the surface if any part fails and causes it to become inoperable. This is discussed in the report on page 37 under the "Protections" section.

Verification

The verification is a critical part of the design process. Due to the scale of the project and the global pandemic, our design work has been focused on getting started on designing and getting initial analysis done on the major components of the robot. The verification of the design is done by virtue simulation and engineering analysis done previously. Thrust calculation, free body diagram, Excel, CFD via FEA were used to determine if our design could meet the specifications.

A quick summary of the analysis section above: The mass of the robot is 100.47 kg which is set to be approximately balanced with the buoyancy force generated by the volume, the pressure on the shell structure under 30m, 293.33kPa, required thrust is 0.366N, the energy consumption of the robot in 3.5 hr is 1907.5 Wh in maximum speed, and the total price of the AUV without Side-Scan Sonar is around $20000.

Based on the preliminary shell analysis, it was determined that the maximum stress experienced by the shell would be 1824 kPa. This is used to calculate the minimum thickness of the shell in polycarbonate required to be. It turns out to be around 0.05 cm. For the balancing weight and practicability of mounting components, we decided to have a 2cm thickness. It should stand pressure under 7-80 meters of seawater easily.

For temperature tolerance, all electronics except sonar, motors are contained in a waterproof housing. This waterproof housing is planned to have an insulation layer to keep the temperature. Also, the temperature tolerances of those electronics are selected to be lower than -4 degree celsius.

The main purpose of this project is to design an AUV which could provide high quality and large seafloor mapping. After researching types of the sonar and their limitations, AquaPix® MINSAS (SAS) is selected to be installed in our AUV. The MINSAS provides a 500m swath during the mapping by employing 337kHz beams, which could be converted to coverage area/h around 0.4626km^2/hr. In the case of resolution, we used the specs sheet in BOM[35-36]. The average SSS along-track resolution is around 0.025m at 0.5 knots. Moreover, this resolution could retain as AUV speeded up to 5 knots. The maximum detection depth of this SAS is 40 m. Therefore, if the AUV wants to map the seafloor at 90 m beneath the sea surface, the AUV needs to achieve at least 50m which is totally valid based on our shell analysis. Overall, AquaPix® MINSAS is able to give us sufficient coverage area and enough resolution for a given speed (0.257m/s) assuming the AUV moves smoothly and parallel to the seafloor.

One of the biggest concerns for our project is the duration time. The minimum duration time has been set to 3.5 hours. From the power analysis, the maximal energy consumption in 3.5 hours is 1907.5 Wh. This estimation assumed that the propellor is fully powered at all times. This won't happen in the real situation since the thrust required to move the AUV is 0.366 N and the maximal thrust could be provided is 100 N. Therefore, the true energy consumption for 3.5 hours of operation would be lower than 1907.5 Wh. The power source could provide 1920 Wh in total. Hence, this robot could at least operate 3.5 hours under the water.

Our robot must remain waterproof in seawater at a depth of 30 meters for at least 3.5 hours, through our engineering analysis we determined the water pressure will be 150 PSI. We decided to use shore 70A durometer rubber as our gasket material and learned that with a 0.25-inch groove cut into the mating surfaces the neoprene needed to be compressed to 45% of its original thickness. 70 lbs of force are required to achieve this requirement, we will compress the surface to 80 lbs because of the importance of this specification on the survival of the robot.

A summary of the verifications for their corresponding requirements and specifications are shown in table B.6.

Project Plan

The project plan we have used throughout this project is summarized through a Gantt chart shown in Figure 18 on page 41. Each step in our project plan is grouped based on the milestones for the project which are based according to the different phases of the ME450 capstone design process framework, and each step includes the anticipated start and completion dates. This was the project plan that we used to compare our current progress with to determine the amount of workload we have left and determine whether we were on track or behind schedule before the Design Expo deadline. It remained unchanged for the duration of the term.

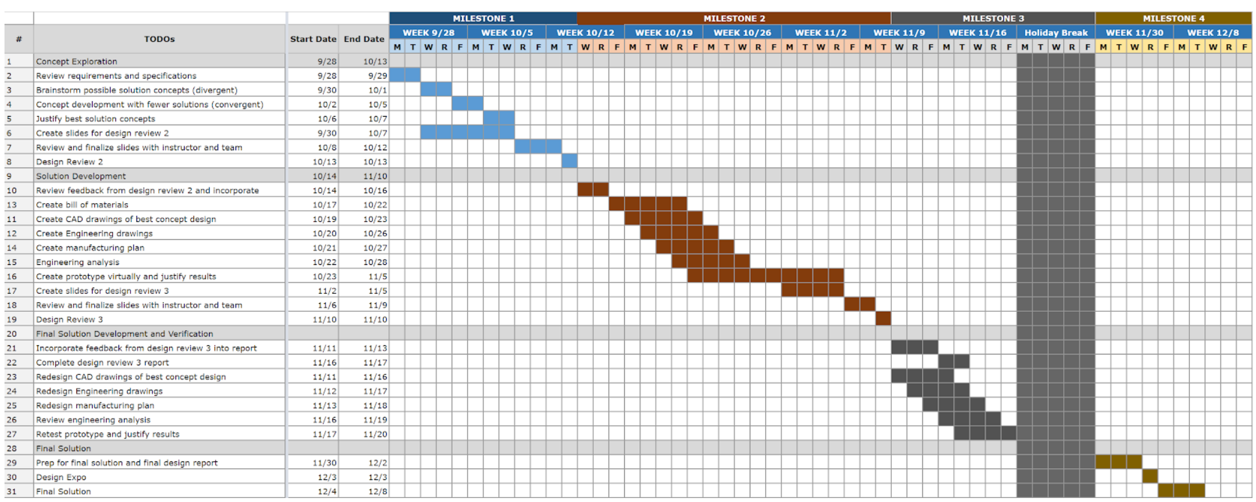


Figure 18. Gantt chart outlining the major milestones for the project and their expected completion date for the Fall 2020 term established at the beginning of the term.

Discussion and Recommendations

Now that work on the project has been completed for the semester, we are able to review and critique the decisions we made throughout the design process and project. It is important to note that the circumstances of the semester our group was unable to perform any prototyping of physical verification, leaving the project to be heavily design focused. With our project being a new, student-led, initiative, we've had to begin our design from scratch, leaving us responsible for many design decisions and extensive research. This vast amount of work required to produce a fully completed and functional design under our given time constraint was an ambitious challenge to take on, and we later had to adjust the scope of our project. With work concluded, we have produced a relatively high-level design with planning for necessary components and subsystems, but lack exact details such as wiring configurations, some component interfacing, and mounting/assembly features. The strength of our design is that it is a simple to understand and low-cost design for an underwater vehicle, that is fairly versatile in its use cases and ability to be equipped with different types of third party sensors and devices. The weaknesses in our design come from a lack of detailed design for some complex systems of the vehicle, and inability to verify certain variables and design choices strictly through simulation.

Our design's weakness with regard to lack of detail in some system designs can be observed with examples such as lack of detailed wiring, mounting layouts, and component interfaces. For some of these issues, our group did not possess the necessary background knowledge to properly design and verify a subsystem, such as with the wiring and internal mounting structures, as the nuances of underwater electronics is beyond the scope of our knowledge. Internal mounting structures were likely also beyond our scope, as they would require full knowledge of all other internal components, which was not achieved. Our design of component interfaces could have been improved if we were to decide on different components and layouts earlier on, but due to the amount of research required and our lack of background knowledge on the topic, component design choices were regularly being adjusted, requiring new interfacing ideas. Some interfaces, such as the electrical connection from the internal transducer to the external side scan sonar arrays, which would need to be reliably waterproofed and able to be disassembled, may have been out of our scope as we did not have a specific sonar or wiring system we could test to verify for waterproofing, and this type of verification is critical and somewhat unreliable to solely simulate. Our vessel design may also have been improved, as our design choice was based on industry standards and thoroughly documented shapes which would be easy for us to learn and work with. If we had greater expertise in underwater vessels and vessel design, we may have been able to determine a shell design that would be more efficient or cost effective to create.

If this project were to be restarted, or continued in the future, we have some recommendations for adjustments to the project process which would likely improve the design choices and ability to verify component and subsystem reliability in the future. With our group being composed of all mechanical engineers from a similar educational background, we weren't as experienced with some of the major design considerations which would be associated with an underwater autonomous vehicle. Because of this, we would recommend the addition of engineers of other disciplines to the team, and most specifically engineers with backgrounds in underwater vehicles and with knowledge of control systems design and application. Researching the conditions and considerations necessary of an underwater environment consumed a great deal of time for our team, and having a team member who is an expert in this topic would be beneficial throughout the design process. An engineer with knowledge of controls systems design and application would also be highly beneficial to the team, as the control system is a critical aspect of any AUV, and this knowledge could help guide decisions and determine which autonomous functions would be realistically achievable if there were a physical component implemented for it.

For specific design recommendations and adjustments, we would recommend working to complete selection of all necessary internal components, subsystems and interfacing before working to adjust external shell and geometry design. This is because the balance of weight to buoyant force is a critical consideration for this project, and with the addition of new components and internal structures there will be a change in weight, requiring adjustments to the vessel geometry and volume to repair this balance. It is unnecessarily time consuming to redesign and verify the vessel for each preliminary internal layout, thus we suggest competing internal design before further external adjustments. We would also adjust requirements and specifications to further specify the location and conditions under which the seafloor mapping would occur, as this would allow for the determination of more detailed environmental conditions and more focused design and verification. Designing for a multitude of water conditions required the consideration and inclusion of components that may not be necessary or effective in other conditions, such as the navigation system which could be less effective in more turbulent waters.

Conclusion

The benefits to seafloor mapping are endless. Mapping allows us to explore and potentially exploit earth's natural resources from the ocean while also preventing disruption to the ocean wildlife. Researchers can use a map of the seafloor to gather biological research information involving the origins of evolution and behavioral data of unknown fish species, locate underwater landslides to help prevent natural disasters like tsunamis, help determine the layout of undersea cables for telecommunication and data transfer, and gather precious metals and fossil fuels. However, as of this year only 13.7 percent of the ocean floor has been mapped at a high resolution and to a depth of 1500 m. The current time and cost estimate of mapping 100 percent of Earth's ocean floor are approximated to be 350 ship years and three billion dollars respectively.

Our project team is looking to design an underwater robot that maps the seafloor in hopes of eventually creating a map of the entire ocean floor. The robot will be designed to be able to map the seafloor at a resolution of up to 1500 meters, cost less than $70,000, operate for at least 3.5 hours and at a depth of up to 30 meters and at a temperature of up to -2 °C, all while operating at a sonar frequency outside of the 30 Hz to 8 kHz range that ocean wildlife communicate at. In doing so, our project team is hoping to decrease both the time and cost to map the complete ocean floor while also improving upon the existing underwater robot solutions. Many underwater solutions map up to a much higher resolution than just 1500 meters but the cost of producing these robots is also much higher. Because the cost is higher, researchers who buy the more expensive robots tend to focus more on mapping the seafloor at much higher resolutions than 1500 meters. By focusing on creating an affordable robot with the ability of recording at a resolution of up to 1500 meters, we are able to contribute to an increase to more than 13.7 percent of the ocean floor up to 1500 meters being mapped.

After adjusting the requirements and specifications to be accurate and feasible for the scope of this class, our team proceeded to the concept exploration process to select the best combination of concepts to pursue for the solution development phase. Starting off with divergent ideation, our team brainstormed, used design heuristics, and used morphological analysis techniques to generate numerous concepts for different crucial systems of an AUV that mostly draws from existing solutions, bio-inspired options with some outlandish options. The process of evaluating the concepts generated for each of these systems were then performed. Most of the evaluation and selection were done by listing and comparing the advantages and disadvantages of each option by focusing on many crucial factors such as feasibility, affordability, meeting requirements and specifications. A few systems such as robot housing and kinematic systems were finalized using a weighted table akin to a Pugh chart to weigh out different options. Through this process, we have selected to build an AUV robot with the following features: a shape similar to those of a typical submarine but with added features such as fins and a pointed nose to represent dolphins, a lithium ion battery as a power source, the side-scan sonar as our mapping tool, and an airbag mechanism that activates automatically when the pressure or weight of the robot is too high when water leaks inside, sending the robot to the surface as a protective measure. Our team decided to use propellers for our kinematic system as shown by the results of the Pugh chart in Table 7 on pages 15-16, but a little more research and evaluation will be needed to confidently determine the specific method of control for using propellers for driving the robot underwater.

After selecting the most desirable and feasible concepts for the solution development phase, our team proceeded to the solution development phase of the design process by designing each major component and system in the AUV individually by attempting to have an initial CAD design of necessary components and perform several analyses and simulations on the design to gauge the feasibility of those initial designs. Initially, most of the designing was heavily geared towards getting the vessel shape and material finalized. Through the benchmarking of existing solutions and their results, our team designed a vessel shape in a common cylindrical submarine-like shape with fins and an NACA0012 airfoil attached, as these structures were proven to be commonly used with credible results in existing solutions. After deciding to use polycarbonate to construct our outer shell, we proceeded to design this outer vessel shape in CAD and established the tools and conditions for running tests on this model going forward. With the kinematics systems, our team designed a mechanism to vary the AUV’s center of mass to improve its kinematics ability and finalized the usage of the propeller to apply thrust, although further analyses have to be done to determine the mass of these new mechanisms and its impact when incorporating them into the AUV. For the power source, our team has analyzed and verified that our selected power source of 48 V 20 A battery packs for bicycles is cheap and provides suitable power to ensure that the operating time specification can be met, but some designing work may have to be done to design a housing or part so that the batteries can be included in the AUV. Finally, our team has determined the materials to ensure that the AUV is waterproofed with some justification about the materials. Because of the aforementioned design decisions above, we were able to fulfill all of the requirements and specifications as detailed in the Verification portion of this document.

Authors

Jonathan Cha is a senior in mechanical engineering from the Bay Area, California. Growing up he was interested in marine biology and was always fascinated by the ocean and its wildlife, but decided to pursue a degree in engineering after discovering in high school that he was much better at math than in biology. He has recently been involved in robotics and student-lead project teams at the University of Michigan.

Juevara Issa is a senior from Flint, Michigan majoring in Mechanical Engineering and minoring in Entrepreneurship. He enjoys tinkering with whatever he can get his hands on, whether it be rebuilding motorcycle engines, building computers, building electric guitars and guitar amplifiers, or learning how to design a plane from the ground up. With respect to community service, he enjoys mentoring underserved youth in the Detroit area and co-founded a community organization designed to motivate primary school students by connecting them with college level athletes. Outside of academics, he has an interest in playing guitar, learning to play piano, reading, boxing, and gravel biking.

Phunyawaj Niamtan is a senior international engineering student from Bangkok, Thailand majoring in Mechanical Engineering and minoring in Electrical Engineering. He is a member of the vehicle, dynamics, and chassis team (VDC) for the Michigan Electric Racing team due to my interests in automobile design and dynamics. In the future, he is most excited about working in a design, analysis, or manufacturing in the vehicle, energy, or the electronics industry. Outside of academics, he is an avid gamer who loves to play all sorts and styles of games. He has a huge interest in anything related to Japanese culture and technology, and I also recently started learning how to play the guitar.

Isaac Smedshammer is a senior mechanical engineering student from Kapolei, HI and he grew up in the Ann Arbor area. He is a member of the Michigan Aeronautical Science Association and has a wide variety of interests and hobbies including travel, food, soccer/football, rollerblading, and building video game controllers. In the future, he hopes to work in the aerospace industry and travel to and live in many different places across the world.

Wesley Voss grew up in Saline, Michigan which is a small town about ten minutes south of Ann Arbor. He has always loved fishing and has been interested in the ocean his entire life. He hopes to go scuba diving one day and is looking forward to seeing robots being deployed in ocean exploration in the future.

Jimin Yang is a senior mechanical engineering student from Hangzhou, China. Due to the interest in control and building a robot, he proposed this project. His interest in marine exploration is derived from watching documentary movies about marine lifes. In the future, he is most excited about designing and building mechatronics devices on his own. Out of academics, he started to learn to play the guitar and analyze data using python.

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Appendices

Appendix A. Data Corresponding to the Problem Definition of Underwater Mapping

Dimensions	52.5 x 36.75 x 15 in (133 x 93 x 38 cm)
Weight (Dry)	166.5 lb (72.6 kg)
Buoyancy	1 to 2 lb (500 g to 1 kg) net positive
Lift Points	4 handles for two-man portability
Depth Rating	100 ft (30 m), 200 ft (60 m) (optional)
Endurance	Up to 3.5 hours with standard payload (no current)
Speed	Up to 0.5 knots (1.5 knots optional)
Energy	1.5 kWh of total energy One 1.5 kWh battery pack Lithium-polymer, pressure-tolerant
Propulsion	Five thrusters for propulsion and control
Navigation	Contact location / relocation; 2 m CEP 50, 1 m CEP 50 (optional) IMU, DVL and depth sensor Hull-relative or seafloor-relative navigation
Communications	Real-time Ethernet via tether (fiber optic tether optional); Ethernet via shore power cable
Safety Systems	Emergency location transponder (optional)
Software	GUI-based Operator Tool Suite Third-party mosaicing software (optional)
Data Management	4 GB removable data storage module (RDSM)
Standard Payload	Sound Metrics ARIS Explorer 3000 Imaging Sonar (1.8 MHz, 3.0 MHz)

Figure A.1. Requirements and specifications for the benchmarked Bluefin HAUV.

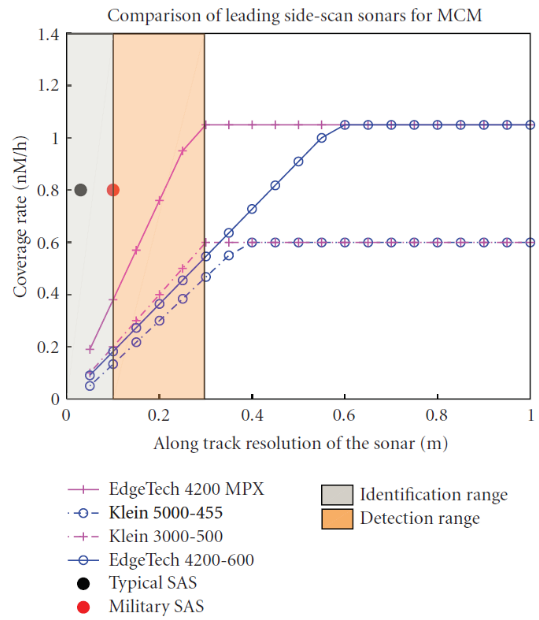

Figure A.2 [8]: Ability to detect and identify targets as a function of resolution and coverage rate (Nm/h: nautical mile per hour) for the best sidescan and synthetic aperture sonars. The SAS sonars here are a typical 100–300 kHz sonar in optimal conditions for synthetic aperture.

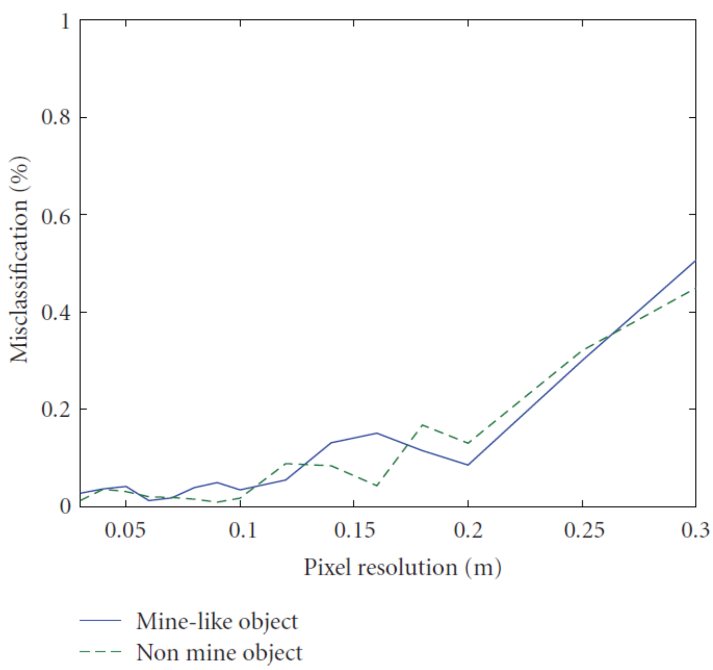

Figure A.3 [8]: Misclassification of the target as function of the pixel resolution.

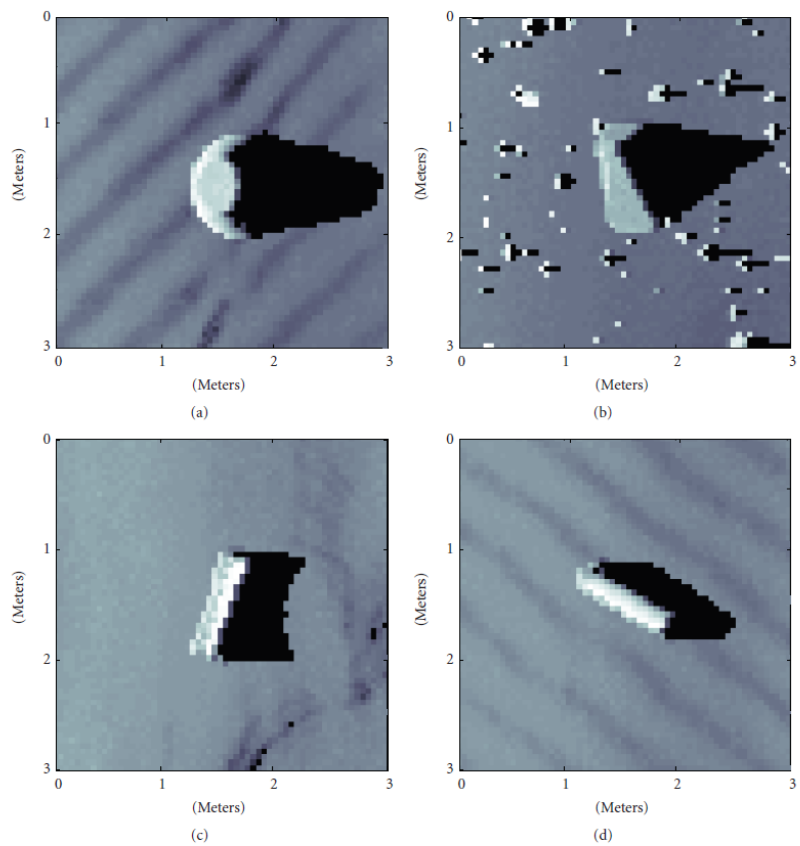

Figure A.4 [8]: Snapshot of the four targets. (a) Manta, on sand ripples, (b) Rockan on a cluttered environment, (c) Cuboid on flat seabed, (d) Cylinder on sand ripples. The pixel size in these targets images is 5 cm.

Appendix B. Full List of Generated Concepts for Each Major System of a AUV Robot

Table B.1. Full list of generated concepts for robot type and power source systems.

Robot Type	Power Source
• AUV (Autonomous Underwater Vehicle) • ROV (Remotely Operated Vehicle) • HROV (Hybrid Remotely Operated Vehicle)	• Batteries • Fuels • Fuel cells • Cable tethered to power generator on boat • Separate power sources for the robot, its subassemblies and other accessories

Table B.2. Full list of generated concepts for design/shape and sonar systems.

Design/Shape	Sensors

● Submarine Design
    ○ Long or short
    ○ Thin or fat
● Box-shaped
● Asymmetric shape
● Cylindrical
    ○ Hemispherical or flat ends
● Bio-inspired
    ○ Fish
    ○ Snake
    ○ Squid
    ○ Jellyfish
	● SONAR
	    ○ Multibeam
	    ○ Side scan
	    ○ SAS (Synthetic Aperture Sonar)
	    ○ InSAS (Interferometric Synthetic Aperture Sonar)
	● Lidar
	● IMU
	● Camera
	● GPS
	● Relative position sensor
	● Depth sensing/pressure sensor
	● Command receiver
	● Weight sensor (to eject and save robot as failsafe)

Table B.3. Full list of generated concepts for the kinematic system and system for protecting components.

Kinematic System	Components' Protection

● Propellers
    ○ Single strong propeller at the end of robot
    ○ Multiple propellers at different locations and orientations
    ○ Rotatable propellers
● Swimming style
    ○ Freestyle
    ○ Breaststroke
    ○ Butterfly stroke
● Bio-inspired kinematic system
    ○ Air "thrusters" that can manipulate orientation
    ○ Reaction wheels with swapping the tail
● Paddle wheel
● Ballast tanks
	● Separate housing for each component and systems of the robot
	● Casings for wire
	● Multiple enclosures
	● Wireless data collection and transfer
	● Flood housing with cat litter or dry ice when water is detected leaking inside the robot
	● Automatic surfacing mechanism
	    ○ Inflatable floating mechanism
	    ○ Emergency engine that shoots robot to the surface
	    ○ Relative position sensor attached to escape capsule

Table B.4. Full list of generated concepts for inner structure and material of AUV robot.

Inner Structure	Material

• Photoresistor circuit to trigger lights
• Sonar/Camera mounting area
• Place for LED
• Waterproof and dry structure for electronics
• Should we recommend using electronics that have a high waterproof rating
• Temperature protection for electronics inside of the robot
• Buoyancy
• Waterproof connection
• Compute board for easy mounting and removal of parts
• Battery housing for easy swapping of battery
• Extra waterproofing housings
• Waterproof casing for wires
• Data storage hardware and housing
	• Ceramic
	• Syntactic foam
	• Alloys
	  ○ Lightweight
	• Plastic
	  ○ Acrylic
	  ○ PLA
	  ○ 3D printing
	• Titanium housings
	• Aluminum/steel pressure vessel
	• Consider material expansion/deformation due to extreme temperatures

Table B.5. Full list of generated concepts for other miscellaneous systems in our AUV robot.

Deployment	Fighting/warding off predator animals	Control method
• From boat • From shore • From air • Torpedo/rocket	• SONAR • Using light • Camouflaging • Great white shark shape/color • Using smell	• PID • Sliding mode control (SMC) • Robust control • Adaptive control • Neural network control • Fuzzy logic controller

Table B.6. Verification of Requirements and Specifications

Requirement	**Specification**	**Verification Method**	**Date/Compliance?**
Quickly obtain a high-quality seafloor map	Speed $\geq$ 0.257m/s	Propellor analysis: Required Thrust$\leq$ Propellor thrust	12/03 - Passed

Quickly obtain a high-quality seafloor map	Resolution of detection ≤ 0.25m Coverage area per hour ≥0.2km^2/hr	Research paper in Side-scan sonar: Fig [A.2]	12/1 – Passed
Quickly obtain a high-quality seafloor map	Be able to map the seafloor 90m below the sea surface	Material property & ANASYS for maximum pressure	12/1 - Passed
Inexpensive	Price ≤ $70000	BOM for Total cost	12/03 - Passed
Durable	Resist pressure 30m	Material property & ANSYS for maximum pressure	12/4 -Passed
Durable	Duration time ≥3.5 hrs	Power analysis for Energy consumption	12/1 - Passed
Durable	Low temperature resistance	Specs for electronics in BOM	12/1 - Passed
Durable	Remain waterproof in saltwater at a depth of 30 m for 3.5 hrs	Waterproof analysis	12/04 - Passed
Harmless to whale	Frequency range should out of 30 Hz and 8 kHz	SAS specs in BOM for beam frequency	12/06 - Passed

Appendix C. Supplemental Appendix

C1. Engineering Standards

For our vessel design, we referenced ASME Boiler and Pressure Vessel Code Section VIII Division 1 for the regulation safety factor to yield for pressure vessels. The stated safety factor to yield is a 4 times, which our vessel exceeds as stated in the Vessel Design Analysis section on page 31.

C2. Engineering Inclusivity

Our team is composed of members of various backgrounds, races, and origin, but these social identities do not affect the power relationship within our team throughout any important phases of the design process. During most decision-making phases (e.g. intended project goals, concept selection, solution development), the decision is made in a closed space through a consensus in which all members feel and think that the decision is optimal, without any member forcing decisions and directions onto the team. Sometimes, decisions are greatly driven by inputs or suggestions from stakeholders and experts, and we always incorporate these inputs or suggestions into our solution in some aspect. Even during the concept generation phase and the research done during the problem and requirement definition phase, every single resource and idea brought up by members are given equal consideration and are appropriately accepted or rejected based on as much factual evidence and data as possible.

One of the largest obstacles to this team's work and progress was the fact that two of our members were working remotely from outside of the United States, which makes meetings difficult to schedule and carry out. Despite the majority of team members being in the United States and living near the university, the availability of the two remote members took precedence as the meeting times often revolved around or decided by when the remote members were available, although the members living in the United States also had some power as we made sure that the meeting times were times where all members were free to attend. Furthermore, due to the time differences, we made sure to limit the time of our meetings to only a couple of hours at most to ensure that all team members can maintain their schedule despite their respective working location and circumstances, and a significant amount of work was completed independently.

One of the aspects of the design process that our team can improve on to be more inclusive is to have more stakeholder feedback than we had during this project's design process. The inclusion of stakeholders in our project was mostly done to gather information about the scope and direction of designing the AUV as this project had no previous sponsors or stakeholders and many of our members initially lacked knowledge and experience of designing an AUV or any underwater vessel. Because of this, we set up interviews with experts in this area only a few times during the problem definition and concept exploration phase to have them recommend ideas and provide feedback on our ideas. Our team did not interact with stakeholders during the solution development phase as decisions were all made according to our decisions and researched evidence along with some feedback from the section professor. In other words, our team can make the design process more inclusive by arranging more inclusive meetings with stakeholders and experts so that they can see the development of our solution, provide corresponding feedbacks or questions, and be informed of future plans or progress so they can feel that they have some form of visible power over certain aspects of developing the AUV.

C3. Environmental Context Assessment

The primary problem that our team's AUV aims to resolve is the issue of seafloor mapping as mapping the entirety of Earth's seafloor is costly and timely. Unfortunately, while this is an ongoing and quite significant issue in the scientific community, it is a less serious and significant ongoing challenge for people outside of the community. People living in underdeveloped conditions (e.g. poverty, malnourished, no education, etc) may not really care or focus on this issue, and resolving this issue of seafloor mapping also does not necessarily improve their living conditions however. However, the issue of seafloor mapping does potentially make some progress towards other unmet and important challenges as outlined by the UN sustainable development goals. One of such goals is the UN's goal of "Life Below Water", which is mainly concerned about protecting the ocean and its biodiversity through the tracking, pollution, and reduction of any and all kinds of ocean pollution. Being able to map the seafloor can help track the extent of pollution in the ocean and its impact on the biome and biodiversity, which can lead to more proactive actions to try to reduce pollution in the ocean. It can also be used adversely to monitor the wellbeing of marine lives or a certain marine creature in the ocean as well. So while the AUV is not directly purposed for combating ocean pollution, it can indirectly be used for ensuring protection of marine life and biome and its results can convince further actions against climate change under the sustainable development goal of "Climate Action" as well. Other than that, the development and manufacturing of this robot can provide job opportunities to create economic growth and stability under the UN development goal of "Decent Work and Economic Growth", as well as potentially pave way for even better or more advanced sonar mapping solutions based on our incorporation and amalgamation of aspects from multiple benchmarked solutions under the goal of "Build Resilient Infrastructure, Promote Inclusive and Sustainable Industrialization and Foster Innovation". However, the impacts on these latter categories are relatively minimal as there are other more effective options to realize these goals, and the AUV's potential to track the status of the ocean's biome and environment, it still lacks any active functions for combating ocean pollution. Therefore, our team assessed that while our AUV can definitely make some progress an important environmental challenge of ocean life protection, it is not to the degree that we consider to be "significant" enough.

The AUV designed by our team is powered by batteries with the only potentially harmful substance being released into the surroundings being the sonar used for seafloor mapping. Because of this, our AUV is a zero-emission robot during its actual usage phase. However, the two 48 volts 20 amp battery packs that act as the main power source for our AUV will need to be charged to about 1920 Wh, or 1.920 kWh within 8 hours, which is expected to incur at least $100 of cost per year for usage every weekday due to electricity usage and potential CO_2 emissions. Furthermore, there are potential environmental costs that is associated with the production of materials like polycarbonate and metals for different components inside the vessel, transportation of the materials for manufacturing and assembly or for deployment of the vehicle, maintenance of the vehicle, and especially the end-of-life disposal of the vehicle due to the AUV containing many potentially harmful components for disposal, which includes battery packs, electronic components, thruster, etc. However, we do not think that the undesirable consequences in its lifecycle will greatly outweigh and overshadow the environmental and social benefits of our AUV given the expected long lifespan of the AUV along with the ability to understand and inspire action to know and protect the ocean environment in a long run without harming the marine biodiversity in the process or at the cost of social freedom or wellbeing (since the mapping operation can be done in remote locations and should not interfere with most common people's lifestyles).

C4. Social Context Assessment

Even though our AUV had no physical prototype as of now, the adoption of our AUV design into the market will definitely positively and negatively impact other stakeholders. We predicted that the major stakeholders who will be positively impacted by the adoption of our AUV design will be any scientists or industries working in the underwater mapping field, as well as any people who are interested or invested in this area of work. An adoption of our AUV design can directly decrease the amount of time required to fully map the seafloor and can help pave way for new technologies and designs for using underwater robots for seafloor mapping, which can potentially promote the use of robots for seafloor mapping and thus decrease the overall cost required for fully mapping the seafloor. We also expected that our AUV design would draw in sponsors or investors in marine technology, provide profit to providers of materials and manufacturing for the AUV, and provide some useful job and learning experience to aspiring or trained engineers as well. Nevertheless, we expected that our AUV will also negatively impact other stakeholders as well. While the frequency of our selected sonar will not disrupt whale communication as listed in the requirements and specifications of our AUV, more research needs to be done to determine exactly the extent of the influence of our sonar's frequency on marine life and environment, if any. In fact, our usage of sonar (and our AUV design, in general) can attract skeptics of sonars and underwater marine robots and environmentalists who may protest against the usage of our AUV design to be certain that our vehicle will not harm marine life in any way.

During its life cycle, our team evaluated that the majority of the AUV's lifetime cost will be attributed to its acquisition and operating costs. The majority of the AUV's acquisition costs are from the purchase of components (especially sonar and the polycarbonate for manufacturing the outer shell) and the majority of the AUV's operating costs come from the cost associated with recharging the AUV's batteries. We also expected some other costs during the AUV's life cycle, such as the transport costs associated with transporting the components and vehicle itself for deployment, maintenance costs associated with fixing or replacing certain parts of the vehicle (which can be huge if the sonar has to be replaced), and some disposal costs for disposing of the AUV during its end-of-life as some components of the AUV are difficult to be recycled for value and the vehicle is most likely, according to our assessment, going to be simply disposed to a potential landfill at the end of its life cycle. However, because our AUV design is not intended for mass production and have a long lifespan during its life cycle, we assessed that our AUV design will be quite resilient to disruptions in business as usual, especially considering the fact that the business sector in marine technology is relatively small and unknown to most common people. Since the market of seafloor mapping is gradually expanding and becoming more advanced, our AUV design which incorporates aspects from multiple benchmarked solutions as well as some relatively modern and new components in our autonomous vehicle from the past 4-5 years, it is quite likely that our solution will be adopted in the market, especially considering that the budget limit we placed on our AUV is based on the average cost of underwater mapping robots available today. Finally, we are certain that our solution will not succeed economically, that planetary or social system will be worse off, as the vehicle itself is still quite a costly and timely vehicle to build and manufacture in the field of underwater sonar mapping that is not economically huge or impactful compared to other industries or engineering fields. Furthermore, the AUV is designed with minimal harm to the environment in mind and the concept surrounding the design of the vessel will most likely not harm the social system in the long run by showing that the AUV do not significantly impact or harm marine wildlife through extended usage and that the design is feasible, not too overly costly compared to other available products, and functions as intended, which should detract criticisms from people who are potentially going to be negatively affected as aforementioned.

C5. Ethical Decision Making

Because our team had a design goal that is driven by the team members, had no previous sponsors, and had no influential or powerful stakeholders overlooking or influencing the direction of our design process, the amount of ethical decisions we encountered and had to consider are relatively smaller compared to other teams due to the deadlines being mostly self-imposed based on the course guidelines and the stakeholders providing mostly suggestions and feedbacks and not imposing strict directions on what to do on our project. Nevertheless, the constraint of the limited resources available combined with the unmovable project deadlines forced us into some ethical situations.

Design-wise, one of the biggest ethical dilemmas that our team faced was the issue of sonar selection. Several requirements were set with regards to what sonar our team should employ, with the two most important factors being cost and effect on marine creatures (which were all listed out in the requirements and specifications for the AUV as shown in Table X). At first, our team found some selections of high-quality and powerful synthetic aperture sonars (SASs) that we think would be optimal to employ for our applications, and our team initially agreed to definitely include one of those types of sonars into our final design. However, by doing some market research and obtaining quotes, we realized that the cost will exceed the budget requirement that we decided upon at the beginning. Because the requirements are directly determined by us and not by a stakeholder or sponsor, we initially considered adjusting the budget specification despite the fact that the requirements and specifications should not be changed often especially when going deep into the solution development phase. However, we ultimately decided to opt for a cheaper sonar that will be within our budget as we consider the real-world implications of our project. Being fickle with the requirements and specifications by constantly altering them will make our project seem aimless and can decrease the confidence of sponsors and stakeholders on the success of our project, which can lead to the solution's failure in the market or the long run. Furthermore, by doing some ethical tests such as the cost-benefit test and universality test, we understand that we only need a sonar that meets the specification we have set (which is considered a pretty clear resolution for underwater mapping) at the lowest possible price for the benefit of corporations and users in order to maximize benefits.

Some other ethical dilemmas that we have to face in regards to our project are the presentation of our project in reports and design reviews. For the second and third design report and design review of the term, our team was behind on some tasks and some of the completed tasks were not finished to the standard that we had hoped, and we were in a dilemma about what to present regarding those incomplete tasks. While we did consider options like omitting details or purposefully making the details of our task vague to hide the details of the tasks that were incomplete, we decided to be truthful and reveal which parts need more work on before they were complete and deliver the full status of our team's progress up until the point of the design report and review. While we realized that doing so would have some negative consequences if it were a real-world project, we recognize that providing untruthful information can potentially have a larger impact on the trust of stakeholders involved and can potentially make them commit to decisions in the future that would negatively affect the development and success of the solution in the future. Furthermore, by being truthful and having ourselves be willing to subject ourselves to whatever consequences from presenting truthful and honest information, we will be more motivated to get future works and tasks done on time.