Ocean Wave Powered Autonomous Boat

Written Report – Virginia Tech and Stevens University

Submitted to: National Renewable Energy Laboratory Department of Energy and National Science Foundation

Submitted by: Virginia Tech partnering with Stevens University

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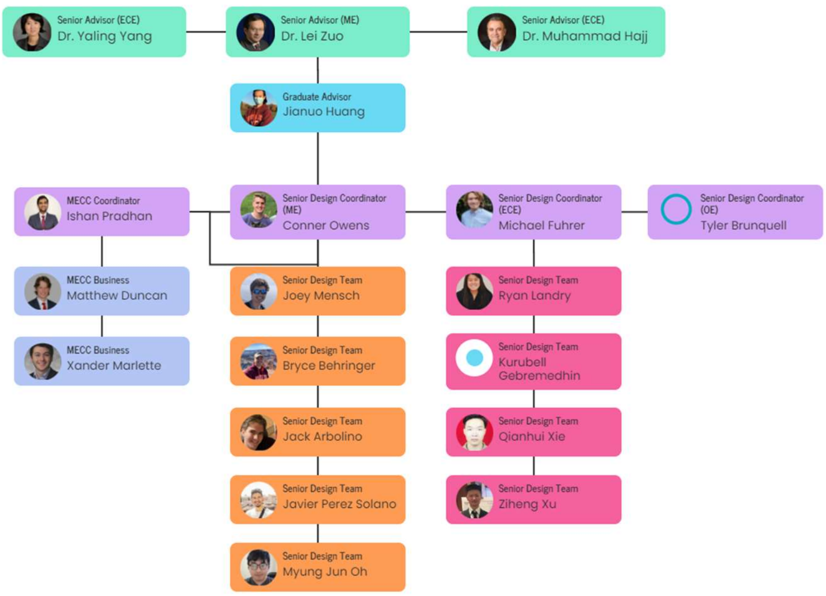

Executive Summary

There is an ever-growing demand for ocean-derived food, materials, energy, and knowledge. For this emerging "Blue Economy" to be successful, it will require access to consistent and reliable power at sea. This project sets out to develop, build and test a wave-powered autonomous robot capable of power generation and storage. This device will act as a mobile aquatic power station capable of providing power to other systems at sea. A commercialized device that can extract power from the ocean can benefit multiple areas, including ocean observation and navigation, underwater vehicle charging, marine agriculture, marine algae, and many more unique applications.

The wave powered autonomous robot will make use of a wave glider mechanism in conjunction with propellers for mobility. This wave glider will have the ability to lock its fins and provide additional functionality as a heave plate. When in the locked position, the wave glider will create resistance to the motion of the boat hull floating up above. This relative motion between the two bodies creates work that will be used to drive a generator and produce power. On board batteries will then serve as an energy storage device to power other devices.

The team's device will be able to reduce the reliance on manned vessels at sea. The device will be capable of covering long distances navigating autonomously to arrive at its destination. It can then start generating power and use this power to provide power to other devices. It can also be tele-operated allowing precise control of the device to perform inspections on offshore structures above and below water. This device can replace manned vessels and it will have lower operating cost than a ship and a crew. It does all this and use sustainable energy to help create a more sustainable future.

Business Plan

B.1 Concept Overview

The Ocean Wave Power Autonomous Boat (OWPAB) is a prototype design for an autonomous ocean vehicle that is powered through harvesting wave energy and redirecting that energy for use in many different applications. The main attraction of OWPAB is to act as an energy storage system that can work in tandem with other products and supplement their need for power through harvesting of wave energy. The potential uses for this product are numerous, as the "Blue Economy " grows the need for a reliable self-generating power source at sea is a necessity. The OWPAB uses a wave glider concept that allows it to lock its fins and function as a heave plate, while simultaneously maintaining the option for passive movement. When locked, the OWPAB will generate energy as the heave plate resists motion to the boat hull floating above which then drives a generator and produces power. The power is then stored in batteries on the vessel that can be distributed to other devices for a range of possible applications.

The OWPAB will be able to reduce the need for manned vessels in the ocean which will decrease operating costs for industries as well as create a safer environment for workers. In addition to being autonomous, OWPAB also has an option to be tele-operated which allows for precise control of the vehicle. Possible applications for OWPAB include ocean observation and navigation, underwater vehicle charging, marine agriculture, inspections of offshore structures, and many more. OWPAB looks towards a sustainable future where energy can be harvested in the ocean and used without the need for fossil fuels.

B.2 Market Deployment Feasibility

B.2.1.0 Market Opportunity

The industry of autonomous underwater vehicle manufacturing is relatively young with high room for growth. Major companies involved include General Dynamics, Lockheed Martin Corporation, Boeing Company, and Huntington Ingalls Industries Inc. with Boeing occupying the highest market share [5]. Other players operate in 46% of the market so there is still high competition outside of the major companies [5]. Capital intensity is low but there is a high importance on technology and ability to adapt to change. This can make market entry somewhat difficult however not overly high. Opportunities in the industry include high revenue growth from 2005-2021 as well as forecasted increase in demand to continue growth [5]. A strong opportunity for our product is that there is increased demand for commercial and scientific use of these autonomous vehicles where many of the major players are in the defence contracting industry, positioning ourselves in a more unique and expanding section of the market [5].

B.2.2.0 Relevant Stakeholders and End Users

Stakeholders include companies that would be interested in the purchase of the Ocean Wave Powered Autonomous Boat (OWPAB), these stakeholders would be considered of high importance and interest as their needs would have to be met with the product. Our product has been designed around three target markets; however, expansion markets and the wider community are all stakeholders for our product.

B.2.2.1 Target Market

B.2.2.1.1 Fish Farms:

Our product has the ability to power fish farming equipment and auxiliary robots replacing the need for dangerous jobs currently done by divers. Allowing for the robot to be placed as a charging pad thus reducing electricity consumption and improving the sustainability of the farm.

B.2.2.1.2 Autonomous Inspection and Surveillance

Our product is mobile and has cameras on it. It can be configured to observe and inspect any at sea element or equipment due to a GPS module as a part of the electronics package that you have such as navigation buoys and offshore wind turbines. All without the need to be refuelled or make someone personally go out and perform the surveillance/inspection.

B.2.3.0 Cost Competitiveness with Alternative Energy Sources

The biggest competition to wave and tidal energy sources has always been wind and solar. Each system has its pros and cons. Solar especially has geographic limitations due to the way in which sunlight hits the planet. As seen in figure 1, when operating at high latitudes, photovoltaic panels are significantly less efficient and thus provide a lot less power simply because the energy density of sunlight hitting the area is reduced. Wave bases systems can provide a steady source of power not dependent on the wind or lighting conditions. A case study conducted in Alaska on the potential of solar panels in the region revealed that there is a dramatic decrease in available energy during the winter months. Additionally, according to the solar energy technologies office, thick clouds and other similar atmospheric conditions can reduce the effectiveness of photovoltaic panels by up to 90% [7].

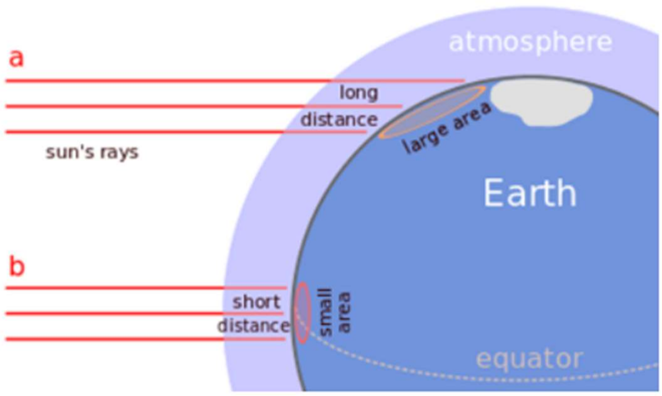

Figure 1: Sunbeam Incident Angles [6]

B.2.4.0 Development and Operations

The team came up with a 4-step deployment plan. As seen in figure 2, the team intends to follow a gradual deployment from development and testing into the domestic market and only then make strides to enter the international markets.

Figure 2: Market deployment plan

B.2.4.1 Research and Development (R and D)

Research and development for this project will continue through a collaboration between the Center for Energy Harvesting Materials and Systems lab (CEHMS) at Virginia Tech, Steven's university, and addition of the Mechanical Engineering department at the University of Virginia. The current research and development plan is shown in figure 3.

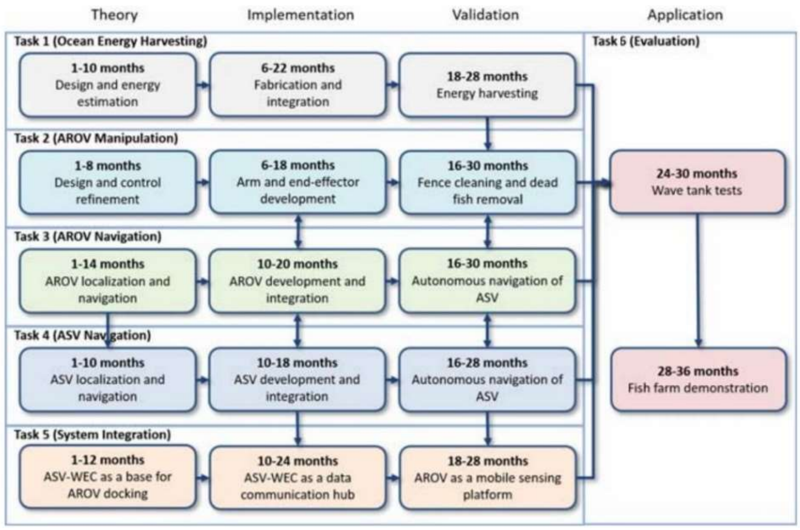

Figure 3: Research and Development Plan

B.2.4.2 Partnerships

The team's advisor Dr. Lei Zuo has been working on similar projects for a long time and has put the team in contact with several key figures in the industry and intends to carry this project forward through as a fully funded project. A proposal is currently underway for a joint project with the United States Department of Agriculture, Virginia Tech, University of Virginia and Stevens University. The key personal involved in this project would be as follows:

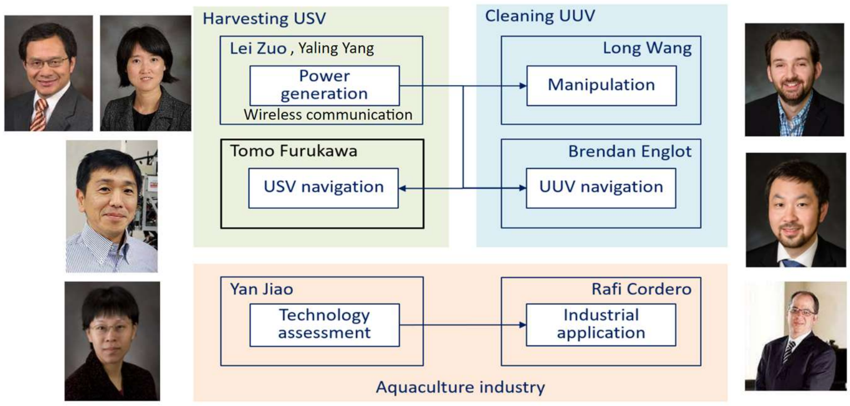

Figure 4: Key Personnel in future partnerships

Virginia Tech's Dr. Lei Zuo and Dr. Yaling Yang would focus on power generation, while UVA's Tomo Furukawa would focus on navigation. Similarly, Steven's Long Wang and Brendan Englot would focus on the use of that power and navigation. Furthermore the expertise provided by Yan Jaio and Rafi Cordero would greatly help in the application of aquaculture and fish farm operations.

B.3 Customer Discovery

Virginia Tech MECC consulted several potential customers within the target markets in order to better understand the market use and demand for the product. This led the team to gain a better understanding of design requirements and target specifications that OWPAB needed to be successful.

B.3.1 Blue Ocean Mariculture

Dick Jones, the CEO of Blue Ocean Mariculture, offered a unique perspective towards how OWPAB could be of use in the ocean aquaculture industry. He explained that currently divers suit up and submerge regularly to clean fishery nets which is often regarded as a tedious job and not ideal as it is a liability to have anyone working underwater frequently. Mr. Jones stated that if there was an option for autonomous cleaning of fishery nets, he would invest in it as it would decrease the payroll allocated towards it as well as make it a safer environment where only occasionally would someone have to suit up and dive beneath the surface. Autonomous cleaning robots for fishery nets already exist but are expensive and have to be connected to a central hub to get supplied power, or they have down time when their batteries need to be recharged. OWPAB would be able to work in tandem with a cleaning robot and suit Mr. Jones' needs because it would be able to move freely and have a larger range requiring less robots than the current model and offer this service with no down time.

B.3.2 Virginia Institute of Marine Science

Virginia Tech MECC spoke to a representative from the Virginia Institute of Marine Science (VIMS). The purpose of this was to determine how OWPAB would be able to benefit their current projects, specifically OWPAB's ability to do observations and inspections. VIMS stated that much of the work they do involves on site observations and tests. The VIMS representative stated that she believes OWPAB could have an important impact on the research and testing they do at VIMS. She said that having the option for an autonomous vehicle would allow for testing and observation 24/7 and without the need for someone to be on site which would be very beneficial. She did state though that OWPAB would have to be financially feasible for implementation as the current system of testing and observation does work so potentially purchasing OWPAB would need to make fiscal sense for their organization.

B.3.3 Orsted

The team also met with Orsted, a renewable energy company that deals with offshore wind farms. Our idea was that OWPAB would be able to conduct observation and repairs to the base of the offshore wind farm if needed. The representative told us that observation with OWPAB would be very beneficial but that repairs might still be done with human interactions as people are already trained in that field and it would probably be easier to get done. He really enjoyed the idea of observation though as many offshore wind farms including the ones at Orsted, require abiding by the endangered species act and attempt to make their windfarms safe for these species or face getting shut down. OWPAB would be able to do remote monitoring missions for this purpose which the representative from Orsted liked because they currently do not have a way to check for that outside of manned visits to the offshore farm.

B.4 Risk Recognition and Management

The team analysed risks in three categories, cost, schedule, and technical. A cost risk is one that where the team's resources are at risk of not being adequate. A schedule risk is one where the timeline doesn't work out as expected. A technical risk is whatever is not cost or schedule, usually something that occurs during operation, like a leak or collision. Mitigation plans are created to deal with these risks, and these plans inform design choice, scheduling, and budgeting.

The team identified two cost risks. The first was that the design could require specially manufactured components, which would be expensive. A way to mitigate this is to create a design which relies heavily on prefabricated parts. This would decrease the likelihood of needing a specially manufactured part, but not the consequence of needing one. The other cost risk was that the budget wouldn't be enough to pay for each subsystem of the boat. To mitigate this risk, nonessential subsystems could be given a maximum budget to reduce the likelihood or severity of spending too much money. This would allow for strong investment in essential systems, like the powertrain.

The team identified eight technical risks. Only the severe ones are discussed here, the rest are in the appendix. The first risk identified was that ocean water could leak into the boat from cracks or poor seals. This would be catastrophic for the boat and would almost assuredly destroy it. To mitigate leaks, the number of joined parts should be minimized which would reduce the likelihood of leaks. In addition, mission critical components (backup batteries and communications) should go in their own individual waterproof compartments which would reduce the severity if a leak does occur.

Collisions with ships, rocks, or buoys are another risk identified. Adding lights would help other ships to see and avoid the robot. Adding a vision/sonar system could enable the boat to actively avoid obstacles.

Another risk identified is that there might not always be enough wave motion to harvest energy. A lack of waves would be dire for the boat because there is always a power draw to the electrical systems and so being unable to harvest for too long would deplete the batteries. A way to mitigate this is to add other renewable energy harvesting methods, like solar panels or wind turbines. One could also add extra batteries if calm waters are anticipated on a mission.

The last high level technical risk is capsizing. A capsize event would be catastrophic for the mission, but it would be unlikely to destroy the boat. The chance of capsizing can be mitigated by constructing a wide boat with a low center of gravity. With the right configuration of width, center of gravity, and center of buoyancy, the boat could be made "self-righting", meaning it would recover from tipping automatically. Every part of the boat should also be made to withstand extended submersion to reduce the consequences of a capsize event.

Two schedule risks were identified. Late shipment on a critical part and being unable to fully test the boat in the Stevens University wave tank. To mitigate the risk of a late shipment, each part ordered must be tracked and its expected arrival date logged. Plenty of time must be allowed for parts to ship, especially now due to supply chain disruption in the wake of Covid. This could be mitigated by maintaining good lines of communication with the team's partners at Stevens. Back-up dates at the tank can be scheduled to avoid timing conflicts.

Most of these risks can be mitigated with design choices, and as such the RAMP has very much informed the design. The boat must be extremely watertight all over, be stable enough to right itself after being rolled 90 degrees, have enough battery capacity to make it through a waveless day, be visible to other ships, and be able to avoid collisions autonomously.

B.5 Financial Analysis

B.5.1 Expenditures

Predicted expenses for prototyping was $5,757.42 in the initial budgeting report, however, expenditures requested totals to $6,124.32 to produce the product prototype. Other operational expenses were incurred with larger expenses being renting a boat for $200 and using a wireless controller for $30. Additional miscellaneous expenses added onto operational and capital expenditures totalled to $7,072.14 spent.

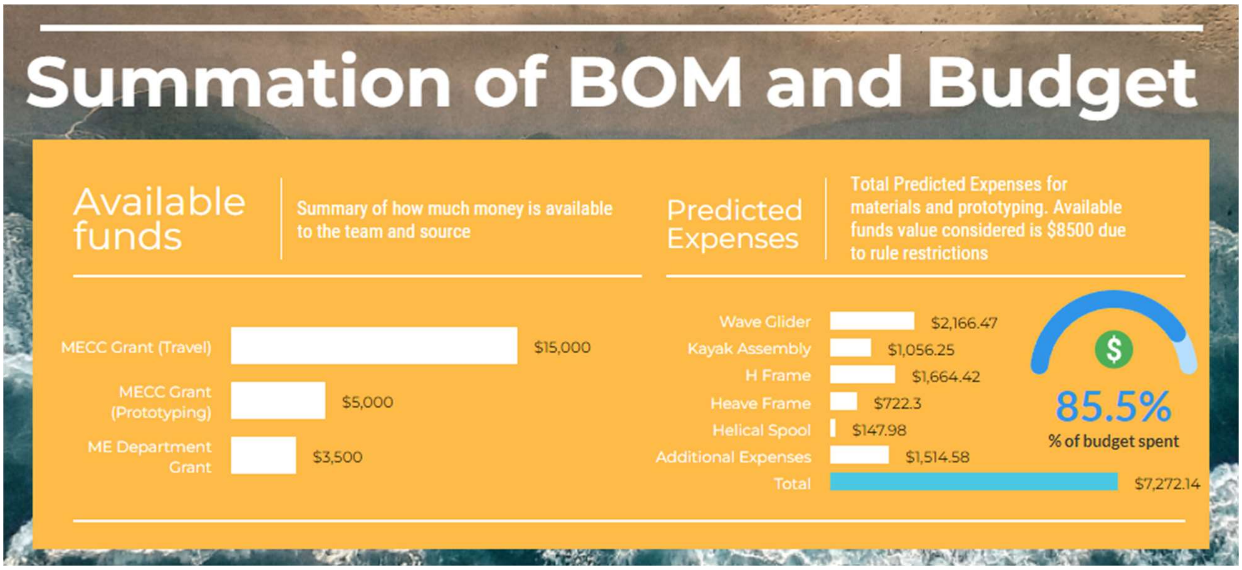

Figure 5: ME Team Budget and Purchase Requests

ECE Team

Purchases of materials and equipment totalled to $1,187.71 with $80 being supplied by the Electrical department, the rest was procured by purchasing from vendors. Other operational expenses included a mobile phone plan being $16 per month for 5 months totalling to $80.

ECE Team Cost Breakdown:

Raspberry Pi 3 Model B	Provided by ECE Dept.	$80.00
Qwiic Iridium 9603N	Purchase	$144.00
RockBLOCK MkII	Purchase	$267.50
MetOcean Iridium SBD Subscription	Purchase	$0.00
RFD 900x-US Modem	Purchase	$196.54
Raspberry Pi Camera Board v1.3	Purchase	$13.99
Arducam for Raspberry Pi Camera Module with Case	Purchase	$12.99
BerryGPS-IMUv4	Purchase	$134.00
MEA-1600-SM	Purchase	$70.40
SG1019NM-915 RF Antenna	Purchase	$86.42
SleepyPi v2	Purchase	$44.70
SMA Cable	Purchase	$18.38
HiLetgo 5pcs IPX IPEX U.FL to SMA Female Pigtail Antenna Wi-Fi Coaxial Low Loss Cable 6 inch	Purchase	$7.49
Polycase ML-46F	Purchase	$38.34
USB to TTL Serial 3.3V UART Converter Cable	Purchase	$14.99
Readytosky 50A Bidirectional Brushless ESC	Purchase	$41.98
Songhe BTS7960 43A	Purchase	$15.99

Figure 6: ECE Team Expenditures and Costs

B.5.2 Product Analysis

Based on the cost of the prototype, estimates on a finalized product could cost from $17,000 - $20,000 to build, selling for around $25,000 - $28,000. Based on the average cost of a dive crew being $89,289 annually, this robot could save a client a lot on management of their equipment. Our robot would also allow clients to negate fuel costs as well as negate costs on the purchase of a larger boat in order to manage their offshore equipment. The only expense needed would be routine maintenance on the robot, allowing our clients to increase profit margins while maintaining quality. Figure 7 shows our assumed variable, fixed, and selling price. Based on this, our breakeven point is at 3 units along with a contribution margin of 20%. If we are looking to target $100,000 of profit, then we will need to sell 23 units.

	Total	Per Unit
Sales (5 units)	$ 125,000	$ 25,000
Less: Variable costs	$ (100,000)	$ (20,000)
Contribution Margin	$ 25,000	$ 5,000
Less: Fixed costs	$ (15,000)	
Net income	$ 60,000	
Contribution margin ratio		**20%**
Variable expense ratio		**80%**
Break-even point		**3**
What-if analysis for target profit		
Target profit		$ 100,000
# of units needed		**23**
Margin of safety		**$50,000**
Degree of operating leverage (DOL)		**0.416666667**

Figure 7: Breakeven Analysis

Technical Report

T.1 Introduction

The kinetic energy available in the ocean is vast and dense. The potential energy of waves along the U.S. coastline are theorized to be as much as 2.64 trillion kilowatt hours or approximately 66% of all energy generation in the U.S. for 2020. While it's important that large scale efforts are made to capture this energy to meet energy demands on land, there is the possibility for wave harvesting technology to be scaled down for other applications. An ever-increasing public demand in ocean-derived food, material, energy, and knowledge has spurred the growth of the "Blue Economy." For the blue economy to flourish, industries will require access to consistent, reliable power that isn't tethered to land based-power grids. A commercialized device that can extract power from the ocean can benefit multiple areas, including ocean observation and navigation, underwater vehicle charging, marine agriculture, marine algae, and many more unique applications.

This project sets out to develop, build and test a wave-powered autonomous robot for applications such as fish farm monitoring, ocean observation and communication, underwater and surface vehicle charging. The device will be a mobile aquatic power docking station with integrated energy generation, energy storage, and propulsion systems. The team will be working closely with an electrical engineering team which will handle the electronics and communication components. In addition, this project is competing in the U.S. Department of Energy Marine Energy Collegiate Competition (MECC). As part of the MECC, the team will conduct market research to identify potential customers where the autonomous boat can solve a real-world need.

T.2 Customer Needs, Engineering Characteristics and Target Specifications

The primary customers for the wave powered autonomous boat are companies that have substantial offshore investments and a need to provide them with electricity. This would include companies in industries such as "ocean observation and navigation, underwater vehicle charging, marine agriculture, marine algae, and many other unique applications" [1]. To create a list of customer needs, the team brainstormed the critical functions of the device and features that would make it more attractive to potential customers. Table 1 shows the list of customer needs the team created. A team of business students at Virginia Tech was recruited to create questions and conduct interviews with companies that have experience working offshore. With the feedback collected from these interviews, the list of needs can be refined to better align with the goals of the customer.

Table 1
Customer Needs

	#	Description	Weighting
Customer Needs	1	Durable	5
	2	Self-Sufficient	5
	3	Transportable on Trailer	1
	4	Launchable on a Boat Ramp	1
	5	Large Charging Capacity	5
	6	Stable in Bad Conditions	3
	7	Maintenance Free Deployment	4
	8	Maneuverable	4
	9	Economically Viable	3
	10	Operable from Shore	4
	11	Modular Payload	4
	12	Long Range Capabilites	2
	13	Fish Enviromentally Friendly	2
	14	Tunable for each Location	4
	15	Recoverable from Failure	2
	16	Low levelized cost of energy	5
	17	Extra payload capacity	3

Weights were applied to each of the customers’ needs based on their perceived importance as seen in Table 1. The team assigned these weights based on their significance towards the project’s success, with the ultimate objective of generating power from ocean waves. Rankings were based on a scale from 1 to 5, where 5 is the most important and 1 is the least important.

A list of quantifiable engineering characteristics was created based on the customer needs to facilitate the creation of target characteristics. These characteristics are shown along the top of Tables 2 and 3. Each engineering characteristic was then correlated with the customer needs according to how strongly they are related. The relationship between characteristics and customer needs is indicated by either a 1, 3, or 9: 1 indicating a weak correlation and 9 indicating a strong correlation. The correlation values for each engineering characteristic were then multiplied by the corresponding weights for each customer need to determine an absolute score for each engineering characteristic. A higher absolute score indicates an engineering characteristic is more important for the success of the boat. The scores show that the most important characteristic is battery capacity, followed by structural integrity and water resistance. The least important characteristic is the operating noise. These scores are used to determine which parts of the project should be given the most attention and to help narrow down concepts towards a final design.

Table 2
Engineering Characteristics Part 1

Engineering Characteristics				1	2	3	4	5	6	7	8	9	10
Customer Needs	#	Description	Customer Weighting (5-1)	Max Speed (Kts)	Battery Capacity (KWh)	Weight (kg)	Bounding Volume (m^3)	Bouyant Force (N)	Average Energy Generated (W)	Max Customer Added Load (kgs)	Cost ($)	Structural Inegrity (FOS)	Movement Efficiency (km/kWh)
	1	Durable	5									9	
	2	Self-Sufficient	5	1	9				9			3	3
	3	Transportable on Trailer	1			3	3						
	4	Launchable on a Boat Ramp	1			1	9						
	5	Large Charging Capacity	5		9							1	3
	6	Stable in Bad Conditions	3				3	9		3		9	
	7	Maintenance Free Deployment	4	1					1			3	
	8	Maneuverable	4	9	1	3	9	3		1			3
	9	Economically Viable	3		3	1			3	3	9		1
	10	Operable from Shore	4		3								
	11	Modular Payload	4		3		1	1		9		9	1
	12	Long Range Capabilites	2		9				3				3
	13	Fish Enviromentally Friendly	2	3									
	14	Tunable for each Location	4			1			9			1	
	15	Recoverable from Failure	2					3				3	
	16	Low levelized cost of energy	5		3				9		9		1
	17	Extra payload capacity	3		1	9	1	9		9		1	1
Absolute Score	------>			51	163	50	64	76	145	85	72	153	63
Importance Ranking	1st, 2nd, 3rd...	------>		17	1	18	14	11	4	9	12	2	15

Table 3
Engineering Characteristics Part 2

Engineering Characteristics				11	12	13	14	15	16	17	18	19	20
Customer Needs	#	Description	Customer Weighting (5-1)	Deployment time (minutes)	Water Resistance (IP Rating)	Charge Time (hrs)	Maximum Harvestable Wave Amplitude (m)	Head on Impact into rigid object (Kts)	Operating Nosie (dB)	Payload Mountable Area (m^3)	Service Life (years)	Roll Angle (Degrees)	Natrual Frequency (Hz)
	1	Durable	5		9			9			3	9	3
	2	Self-Sufficient	5		1	1	3				9	1	3
	3	Transportable on Trailer	1	3									
	4	Launchable on a Boat Ramp	1	9									
	5	Large Charging Capacity	5			9				3			
	6	Stable in Bad Conditions	3		3		3	9				9	1
	7	Maintenance Free Deployment	4	1	3					3			
	8	Maneuverable	4		1							3	
	9	Economically Viable	3	1		3				3			3
	10	Operable from Shore	4							1			
	11	Modular Payload	4		9					9			
	12	Long Range Capabilites	2		1	3				3			
	13	Fish Enviromentally Friendly	2						9				
	14	Tunable for each Location	4		3	9	9			9			9
	15	Recoverable from Failure	2	3	9			3			3	3	
	16	Low levelized cost of energy	5	1		3							9
	17	Extra payload capacity	3		1					9			1
Absolute Score	------>			30	146	116	60	78	18	145	66	95	126
Importance Ranking	1st, 2nd, 3rd...	------>		19	3	7	16	10	20	5	13	8	6

Lastly, the team determined target specifications for each engineering characteristic as a metric for measuring the success of the final design. Each target specification is given a marginal value and an ideal value along with a method to measure performance as shown in Table 4. The marginal value is the target the team believes to be the most realistic, while the ideal value may not be achievable within the limits of this project. Both values were determined based on the performance of currently available technology along with the judgement of the team according to difficulty in implementation and time constraints. Some target specifications needed to be revised later on in the design process according to new information. For instance, the ideal battery capacity had to be lowered from 100 kWh to 10 kWh after the budget planning process showed a battery of that size would be far too expensive to build a full-scale prototype.

Table 4
Target Specifications and Verification Devices

Target Specifications Table						
Customer Need #s	Eng. Characteristic	Importance	Units	Marginal Value	Ideal Value	Verification Measurement Device
2, 7, 8, 13	Max Speed	17	Kts	3-5	6-7	GPS
2, 5, 8, 9, 10, 11, 12, 16, 17	Battery Capacity	1	kWh	2 kWh	10 kWh	Multimeter
3, 4, 8, 9, 14, 17	Weight	18	kg	1000	500	Scale
3, 4, 6, 8, 11, 17	Bounding Volume	14	m^3	25	18	Measuring tape
6, 8, 11, 15, 17	Bouyant Force	11	N	10,000	20,000	Submersion tank
2, 7, 9, 12, 14, 16	Average Energy Generated	4	W	10	100	Multimeter
6, 8, 9, 11, 17	Max Customer Added Load	9	kg	50	200	Scale
9, 16	Cost	12	$	$250,000	$100,000	Cost Analysis
1, 2, 5, 6, 7, 11, 14, 15, 17	Structural Integrity	2	FOS	4	9	FEA
2, 5, 8, 9, 11, 12, 16, 17	Movement Efficiency	15	W/mi	0.5	1	GPS + Multimeter
3, 4, 7, 9, 15, 16	Deployment time	19	min	20	10	Stopwatch
1, 2, 6, 7, 8, 11, 12, 14, 15, 17	Water Resistance	3	IP rating	7	8	Submersion tank
2, 5, 9, 12, 14, 16	Charge Time	7	hr	23	12	Stopwatch
2, 6, 14	Maximum Harvestable Wave Amplitude	16	m	2	5	Wave Tank
1, 6, 15	Head on Impact with Rigid Object	10	J	3-5	6-7	Crash Test
13	Operating Nosie	20	dB	100	50	Decible meter
5, 7, 9, 10, 11, 12, 14, 17	Payload Mountable Area	5	m^3	4	6	Measuring tape
1, 2, 15	Service Life	13	Years	1	5	Simulation/Analysis
1, 2, 6, 8, 15	Roll Angle	8	Degrees	30	90	Protractor + Pendulum
1, 2, 6, 9, 14, 16, 17	Natrual Frequency	6	Hz	0.25-1	0.1-2	FEA

T.3 Concept Generation

The importance of concept generation was well understood within the team. The two most important components of concept generation are to generate many ideas and to not rule out any for being too ridiculous or challenging. Once the team had a substantial number of ideas created, a number of analytical methods were used to narrow down the collection of ideas to the best ones.

Concept generation began with creating a mind map. Several sub-functions were developed to begin. These functions were categorized to cover every major function of the ocean powered autonomous robot. The first and most important sub-function is "Generate Power." The boat must be entirely self-sufficient, so choosing the best way to harvest energy is necessary. Energy could be generated from ocean waves, ocean current, solar, nuclear, hydrocarbon, or wind. No more than 49% of generated energy can come from sources other than the ocean, so the teams focus was on ocean waves. A few examples of brainstormed ideas for harnessing wave energy are a tuned mass damper, an oscillating water column, and a wave snake. Solar panels and various kinds of turbines are potential ideas for supplemental energy generation. Another sub-function is "Boat Structure." This function includes hull types such as catamaran, trimaran, and single hull. It also includes functional structures such as keel and hydrofoil. The other sub-functions include "Mobility," "Store Energy," "Controls," "Communications," and "Modular Mounting." The mind map that shows each sub-function and solutions is shown in Figure 8. This mind map exercise gave plenty of sub-function solutions to be used in the development of a variety of concepts.

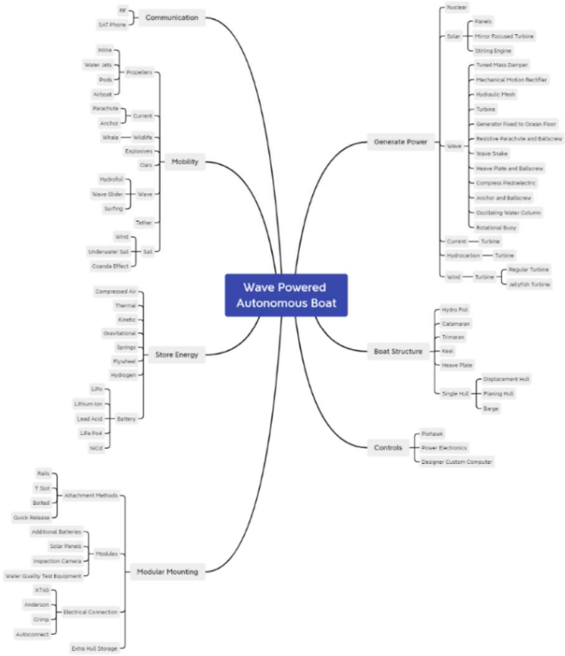

Figure 8. Mind-Map for early brainstorming of sub-functions and sub-function solutions.

Using the 3-7-6 method enabled the rapid creation of several concepts. Each of the seven team members began by generating three unique concepts. Then, the concepts were rotated around the table where each member would have two minutes to make comments and additions. Figure 9 shows the results of this 3-7-6 method for one of the group members original ideas. The left and center concepts in Figure 9 feature a heave plate energy generation method. A heave plate has a large resistance to heave, vertical motion through water. When the boat and heave plate are not directly fixed, it causes a great amount of relative motion. In the left most design, the heave plate has two shafts that run through the boat hull with generators inside them at the plate end. The center design features a circular heave plate with only one shaft. The right design emphasizes an outrigger method of energy generation. The outrigger would fall and rise from passing waves to drive a generator. Some comments suggested side rails for the mountable payload and other comments detailed a better location for a generator.

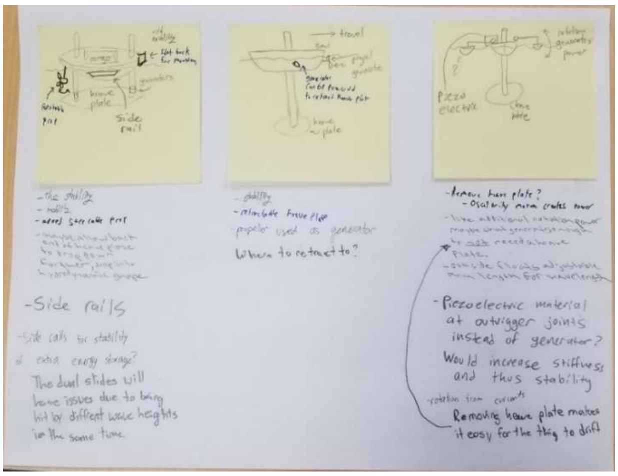

Figure 9. 3-7-6 Method results for one team member’s concepts.

Another helpful concept generation tool was the morphological chart. This chart directly combines sub-function solutions to create unique concepts. The morphological chart, shown in Figure 10, shows many unique combinations of sub-function solutions. The sub-functions are locomotion, boat structure, ocean energy harvesting, power train, energy storage, steering, and auxiliary energy harvesting. The blue path is characterized by a catamaran style boat, propellors for motion, and a wave snake for ocean wave energy generation. A wave snake functions by using hydraulic cylinders placed on the snake joints that extend or retract based on the changing angle between two links of the snake. Figure 11 shows a detailed sketch of what the blue path concept would look like.

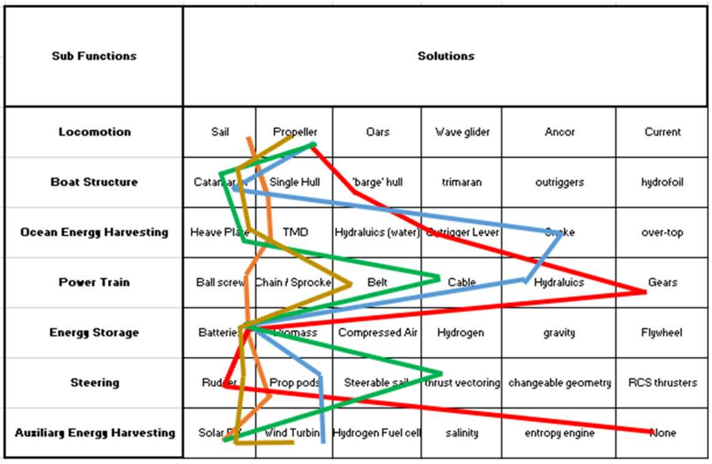

Figure 10. Morphological chart detailing several unique combinations of sub-function solutions.

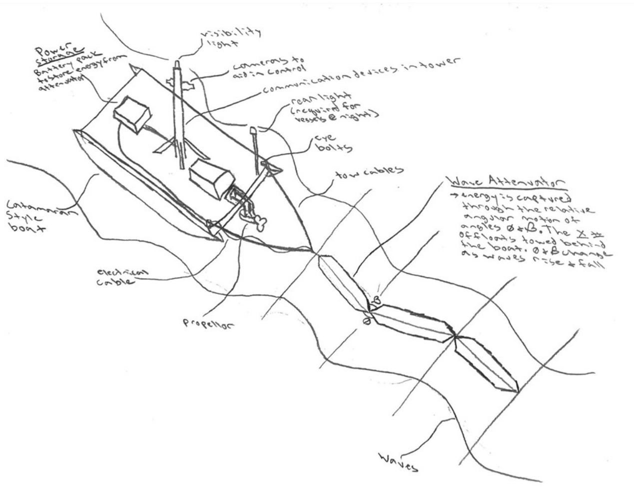

Figure 11. Combination sketch based on the blue path of the morphological chart.

With the aforementioned brainstorming and concept generation methods complete, many other concepts were created from additions or altercations to previous ideas. It is reasonable to say that over 100 concepts were generated. It was quickly ruled out that a wave snake would not work. They are too large and would provide an incredible amount of drag. The outriggers were also discarded early on. The outrigger concept requires that the arms be roughly one half of the wavelength of the wave. The average wavelength of an ocean wave in the Gulf of Mexico and the Caribbean is about 70 meters [2]. This distance is too large for outriggers to be feasible. One consideration was how much power using a propellor would take away from the useful stored power. This led us to think of ideas with wave gliders or sails to cover long range motion with a propellor for short travel. Figure 12 demonstrates a unique concept. This features a heave plate with wave glider fins on it. The wave glider fins flip up and down when being pulled vertically through the waves to provide forward thrust. This idea also includes a helical spool with rope and a mechanical motion rectifier (MMR) as its power train. Figure 13utilizes a heave plate to generate energy and a rigid sail to achieve motion. This design, however, features a foldable heave plate. One concern was that in motion, rocking forwards and backwards would expose more area of the heave plate to the motion and create a massive drag force. Folding the heave plate could help eliminate that issue. Overall, this concept generation process gave several design possibilities that enabled the progression to down selection.

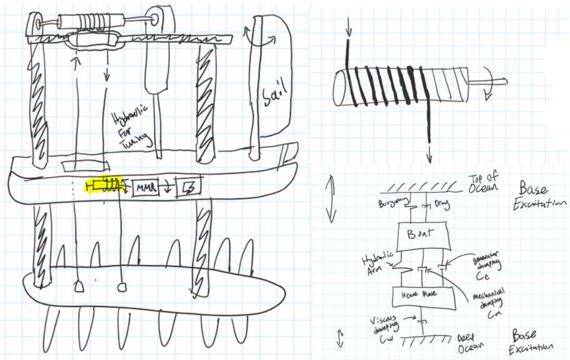

Figure 12. Concept featuring heave plate wave glider combination with spool and rope MMR.

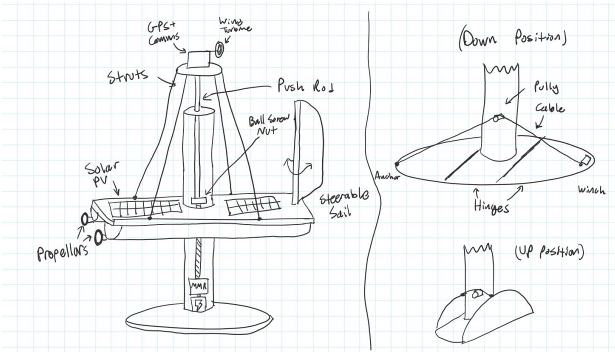

Figure 13. Concept design featuring a foldable heave plate, an MMR, and a sail.

T.4 Concept Analysis

The concepts that were generated are all options that have their pros and cons. Analysis, and prototyping can provide insights that will help narrow down which concepts will work.

One prototype that is being discussed is the helical spool design. The helical spool is a cable driven transmission called a capstan.

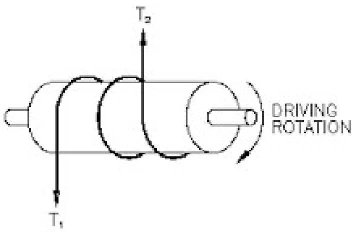

Figure 14: Cable Capstan [3]

This device provides a direct way to convert linear motion into rotational motion. One problem is that the cable drifts back and forth on the capstan as it rotates. This could cause misalignment if not handled correctly. The team wanted to run an analysis on the amount of lateral movement of the cable. A MATLAB script was created to calculate the cable walk. The team found that the cable walk was manageable for higher spool diameters. A diameter of 3 inches will suffice for the team.

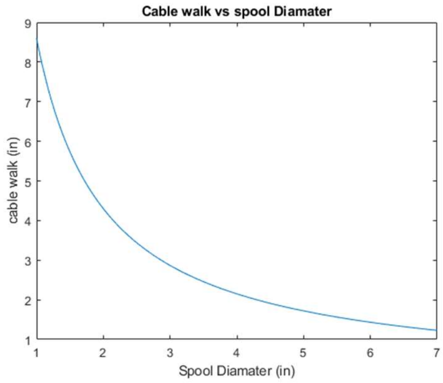

Figure 15: Cable Walk vs. Spool Diameter

Another mitigation of cable walk was found by looking into a Stanford's robotics lecture. The ends can be offset by a specific distance to allow for corrections in the lead angle into the spool. This mitigates the need to compensate cable walk by any mechanical means which simplifies the system.

The diameter of the spool diameters effects the amount of tension in the cable and thus load on the shaft that the spool is held on. This was of interest to the team because the shaft needs to be correctly sized to accommodate the load. Using the max output of a generator and gearbox assembly that a team has in the lab. It was found that the spool can experience a maximum of 1100 in-lbs of force not including inertial effects. Inertial effects will be small because of the sinusoidal nature of waves. With a 2-inch spool, the tension in the cable would be 1100 lbs. This number can then be used in simulation and analysis of other systems.

Once the cable walk and tension were proven to be manageable the team then decided to look at whether they would achieve a reasonable RPM to spin the generator. This can be calculated by finding the number of rotations the spool goes through in one up and down motion. For this calculation it is assumed that the wave height will be 2 meters in amplitude and will have a period of 9 seconds. This is a typical number for ocean waves [4]. Using this data an analysis can be performed on the average RPM the spool would spin at for a certain spool diameter. The data shows that a 2-inch spool produces about 100 RPM average. 100 RPM was within target range of what the team was going for based on graduate students' advice and experience.

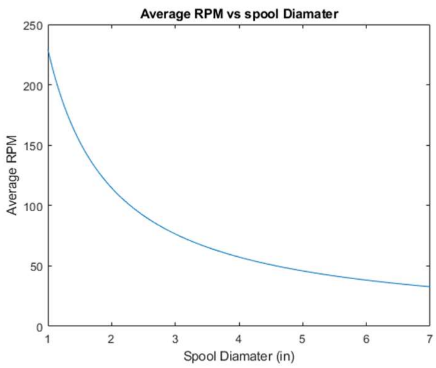

Figure 16: Average RPM vs Spool Diameter

More analysis was performed on the device when it was being constructed and assembled. The report details this further analysis after the Detailed Design section to let the reader become comfortable with the design before looking at component analysis.

T.5 Detailed Mechanical Design

The detailed design very closely resembles the conceptual design. The design can be broken down into 3 large components, the "H-frame", "heave frame", and wave glider. The H-frame is the black structure as seen in Figure 17. The H-frame is constructed out of 80/20 t-slots and primarily serves as an attachment point for other components. At either side of the H-frame is mounted a prefabricated kayak. Sourcing prefabricated boat hulls will not only cut down on manufacturing time in the spring but will ensure the hulls are water-tight before any modifications. Adjacent to each kayak is a propellor. These propellors will be used in conjunction with the wave-glider for maneuverability and propulsion. By varying the power supplied to the propellors, the structure will be able to steer. It should be noted that these propellors are not intended to be used as the main source of propulsion for the craft. This would consume too much power and would be counter-intuitive for the goal at hand.

Figure 17. Detailed CAD Model

The helical spool is another component supported by the H-frame. The spool is mounted to a 1-inch diameter, 60-inch-long steel shaft which feeds directly into the generator sitting on the left kayak. It is held to the H-frame by two shaft supports, an exploded view of which is shown in Figure 18. The helical spool is comprised of two components – metal hexagon nuts and the 3D printed spool itself. This was done to ensure the spool was properly secured to its shaft and would not slip. The metal nuts will be welded to the shaft and the 3D printed spool will sit flush over the nuts. The alternative to this design was to manufacture the spool itself out of metal which would not be feasible with the equipment and budget at disposal. Another solution was to manufacture a metal rod which had a hexagon section in the middle where the spool would sit. This would require purchasing a large diameter shaft and milling down much of its diameter and leaving the hexagonal shape in the middle. Once again, this solution seemed improbable given manufacturing methods.

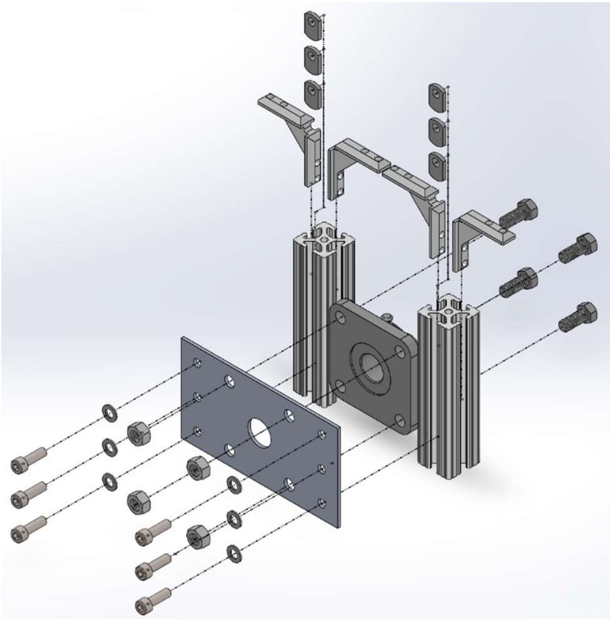

Figure 18. Shaft Support

The last component mounted to the H-frame is a set of rollers. These rollers will be custom manufactured out of polyethylene and sit flush against these set of PVC pipes. An exploded view of a roller is shown in Figure 19. The structure consisting of PVC pipes and metal plates is known as the "heave-frame." These rollers will ensure that the heave frame is able to easily glide up and down on the heave frame. This is crucial because it is this vertical up and down motion which will be converted into rotational motion to drive the generator by the spool.

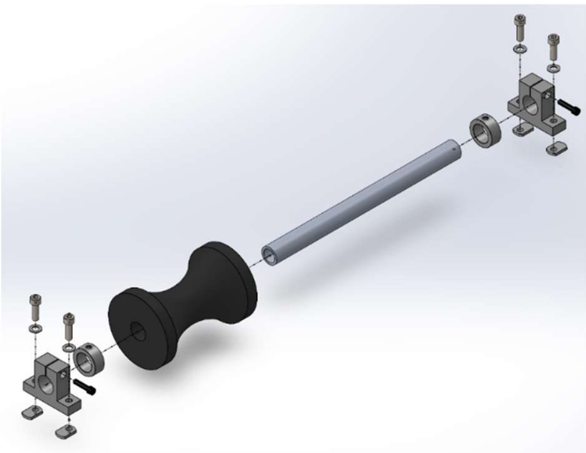

Figure 19. Roller, shaft, and 80/20 mountings

The inside of both kayaks will be kept watertight using an HDPE cover that is plastic welded and sealed with silicon. Figure 20 shows the left kayak which houses a welded motor mount with the generator attached. Beneath the HDPE cover is an 80/20 support structure to provide support from the downward force on the shaft. Also in this kayak are two car batteries held together and fastened to the kayak with metal straps.

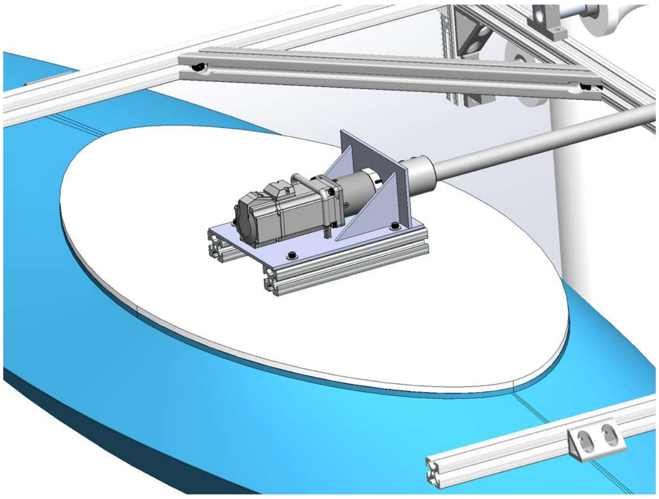

Figure 20: Kayak Cutaway

At the base of the heave frame sits the heave plate with wave glider capability. The body of the heave plate and wave glider is made from aluminum c-channel. There are three sets of fins connected through the c-channel on a steel shaft. The fins are made from half of a folding table that is welded to the shaft with weldable shaft collars. Inside the c-channel is a scissor lift mechanism. This scissor lift is controlled from a linear actuator and push rod that sets at the top of the heave frame. Each shaft has a set of pin blocks fastened to them. These blocks catch the top and bottom of the scissor lift and stop the shafts from moving. Thus, by adjusting the scissor lift, the shaft can be adjusted from completely fixed in heave plate mode to a range of motion such as plus or minus 45 degrees. Figure 21 shows the heave plate and wave glider. Figure 22 shows the scissor lift and pin block shaft locking mechanism.

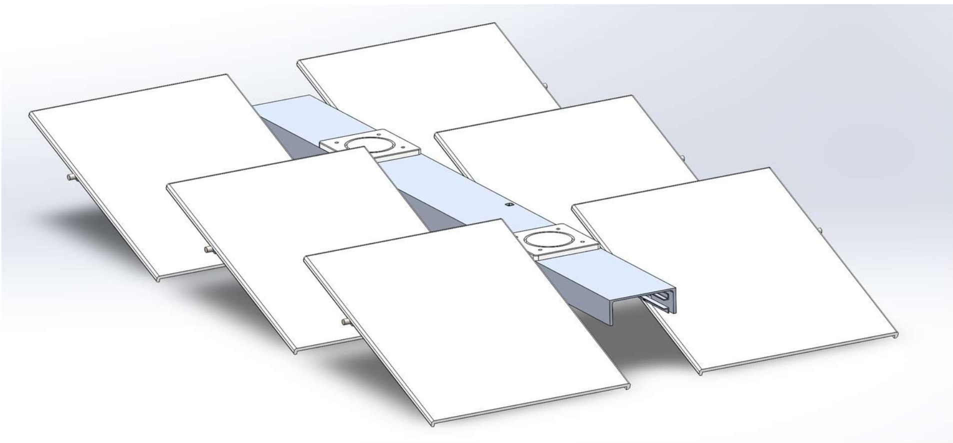

Figure 21: Wave Glider

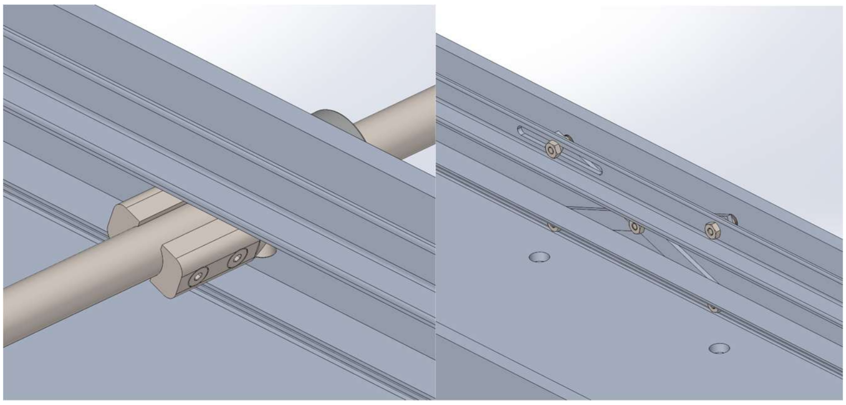

Figure 22: Locking Mechanism Showing Unlocked and Locked Positions

T.6 Detailed Electrical Design

The design also includes electrical work. This robot will require a lot of programming and communication protocols. This would be too much work for one team that is why the project also has in ECE team accompanying the ME team. This lets the mechanical team focus on designing the actual mechanism. There will also be a grad student focusing on the power electronics for the robot. The mechanical team has enough work on their plate for the rest of semester and the electronics for power generation is very difficult. A grad student will accompany the team to design the circuitry required. The team will be in close communication as to keep the design heading in the correct direction. Figure 23 shows the electrical schematic created by the ECE team. This mostly focuses on communication protocols and computation, but it is possible to see where the ME team will need to interface to the ECE's electronics.

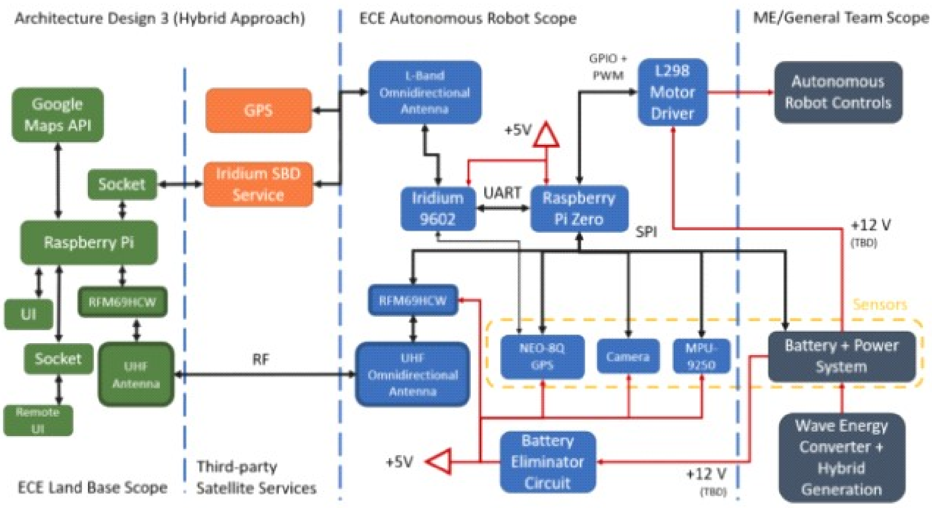

Figure 23: Electrical Schematic Including ECE Components

T.6.1 Packet Datagram

There are three main objectives of our packet's datagram: to a) enable our communication system to implement reliable flow control, b) to enable applications on either side of the link to interpret the serialized binary data, and c) minimize data overhead. For reliable data transmission and flow control, our datagram contains a preamble, packet ID, packet length, and checksum. For application interpretation, the datagram contains a single *Type* byte to designate how the binary data should be interpreted; refer to Figure 24 for a list of considered message types.

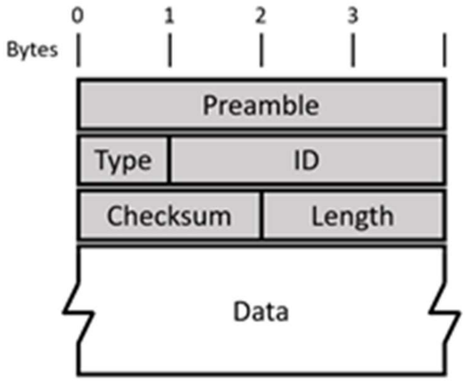

Figure 24: Layout of 12-byte datagram header.

Table 5:

Table of Message Types

Message Type	Hexadecimal Value	Description
Null	0x00	Data w/i packet is meaningless and should be ignored
Handshake	0x01	Used by comm. system to initialize a connection. Forwarded to high-level applications to notify a connection has been made.
Handshake Response	0x02	Used by comm. system to confirm a connection. Forwarded to high-level applications to notify a connection has been made. Necessary to use a separate "response" type because handshake behavior is stateless.
Selective Acknowledgement (SACK)	0x03	Used by comm. system to acknowledge a packet has been received by other party during a RDT connection.
Duplicate Ack. (DACK)	0x04	Used by comm. system to acknowledge a packet that has already been acknowledged. Interpreted the same as SACK by the recipient of the DACK. Useful for debugging purposes.
Cumulative Ack. (CACK)	0x05	Used by comm. system to acknowledge all recently transmitted packets with and below the provided ID. *Currently not implemented.*
Text	0x06	General text data.
Info	0x07	Non-critical application data.
Error	0x08	Relay critical application failures.
GPS Data	0x09	Data contains robot's longitude, latitude, and compass information.
Image	0x0A	Data is a H264 encoded video frame for live video.
Motor Command	0x0B	Data contains two float values ranging from -1 to 1 to directly power motors. Used for live control.
GPS Command	0x0C	Data contains GPS longitude and latitude, sent by the land base, to which the robot should autonomously navigate.
Motor Switch Command	0x0D	Manually selects between the robot's heave-plate and wave-glider modes. *Unused.*
Control Request	0x0E	Indicates that landbase wishes to start/stop live control. Robot will begin/stop sending live video frames and processing motor commands.
UDP	0x0F	Data is from a 3rd party UDP packet to be forwarded to the other party. *For demonstration purposes currently; planned for AROV integration.*
Heartbeat Request	0x10	Sent from land base periodically test comm. link with expectation that robot will respond with a heartbeat. Land base initiates this behavior (instead of robot autonomously sending heartbeats) to allow land base to monitor latency without time synchronization with robot.
Heartbeat	0x11	Response to heartbeat request. Contains status information like current state (idle, live control, autonomous navigation), GPS data, compass direction, and battery percentage.
Comm. Change	0x12	Forces the other party to change communication mode to the one specified in the data. *Unused.*

T.6.2 Packet Flow

Because our radio link is unreliable and our satellite link is assumed reliable, our communication system contains a demultiplexer to send a packet reliably (using a RDT protocol we implemented and discussed below) or unreliably (simply writing the packet to the communication device).

The first condition that determines how a packet is sent is its specified communication link. Within our Python *Packet* object, an application can specify through which medium, either radio or satellite, the packet should be sent. Packets that will be sent over radio will be sent reliably through our RDT protocol (if the second condition allows); packets sent over satellite will be unreliably forwarded to the satellite handler. Allowing an application to specify over which medium to be sent is useful in the case where the robot and land base are communicating over satellite, but the robot is also retransmitting a handshake over radio in an attempt to establish a faster connection.

The second condition is based on the packet's type: images and motor controls, due to their time-sensitive nature, are sent unreliably to prevent a back-log from forming in the case the radio link fails temporarily. Comm. system specific packets like acknowledgements and handshake responses are also sent unreliably to prevent recursion (e.g. needing acknowledgements for acknowledgements).

T.6.3 Reliable Data Transfer (RDT) Protocol

Our RDT protocol follows the Selective-Repeat ARQ protocol to create a reliable link over radio. This protocol specifies using a 'transmission window' to allow multiple packets to be sent in quick succession, allowing multiple in-flight packets before any acknowledgements are received.

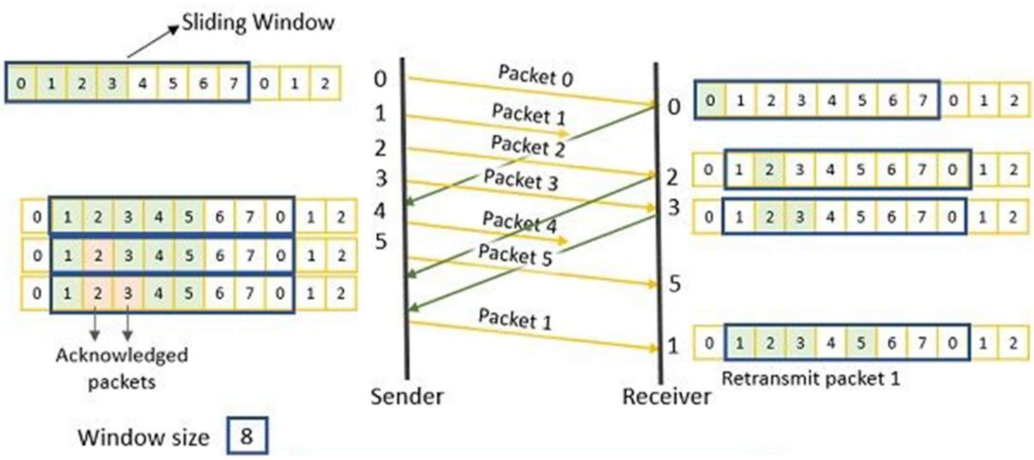

Figure 24: Selective Repeat diagram showing multiple in-flight packets being acknowledged non-sequentially.

Using this protocol, our radio can resend any unacknowledged packets automatically. Additionally, we use CRC-16 checksums to enforce data integrity within a packet.

T.6.4 Handshake Behavior

To allow robot and land base to coordinate which link to communicate across, we created a handshake protocol. When both the land base and robot start, they start up in a special handshake mode in which only handshake and handshake responses may be sent and received. In this mode, the robot will continuously transmit handshakes over radio every 10 seconds and once over satellite. The land base will generate a handshake response over the link it receives the first handshake to arrive as well as changing its primary communication mode to that link. Once the robot receives the handshake response, it will do the same, changing its primary communication link to that it received the response over.

Any packet without a link specified by the application will now be sent over the agreed link, however packets may still be sent over either medium. This allows the robot to continuously retransmit handshakes over radio when its primary communication link is satellite in an attempt to establish the faster link. In contrast, if a party using radio receives a handshake over satellite, they will ignore it.

High-level applications may return the communication system back into its original handshake mode for any reason (e.g. haven't received a heartbeat / heartbeat request for a specified time).

T.6.5 Implementation and Threading

Our communication is instantiated in Python using two threads, handling outgoing and incoming packets respectively, to improve speed and allow the application-layer scripts to operate asynchronously. Python's multiprocessing library was considered, and used at one point, however using interprocess pipes for coordination with application-layer scripts created burdensome overhead - both computationally and organizationally. However, multiprocessing may be a worthwhile approach for future instantiations of similar communication systems.

Additionally, using C++ or similar languages are better suited for the binary-level data handling seen in our communication system, but we chose Python in interest of development time.

T.6.6 WebGUI

The WebGUI is created using HTML, CSS, and JS. Since the user interface needs to use the communication system that was built, a script was created to act as middleware between the two systems. This script utilizes Flask which is a micro web framework written in Python. This allows the GUI to send HTTP requests to the Flask script whenever a user hits a button to send a command. When the Flask script receives these requests, it can then create message packets to send using the communication system.

In order for the robot to also be able to communicate back with the user interface, several web sockets had to be made. One web socket was created for live video, and one was created for messages and data. These were created separately because it helps distinguish the different types of things that are being sent. The data web socket is where all of the GPS information will be sent from. This allows the user to see in real time where the robot is located and what direction it is facing.

Creating these web sockets also allows multiple users to be able to interact with the user interface at one time from different devices. See MECC outreach considerations in section X for more details.

After completion, the WebGUI is able to display GPS information and live video. It also allows the user to enter coordinates for autonomous movement, control the robot using the buttons, and shows all messages being sent and received by the robot.

T.6.7 Electronics

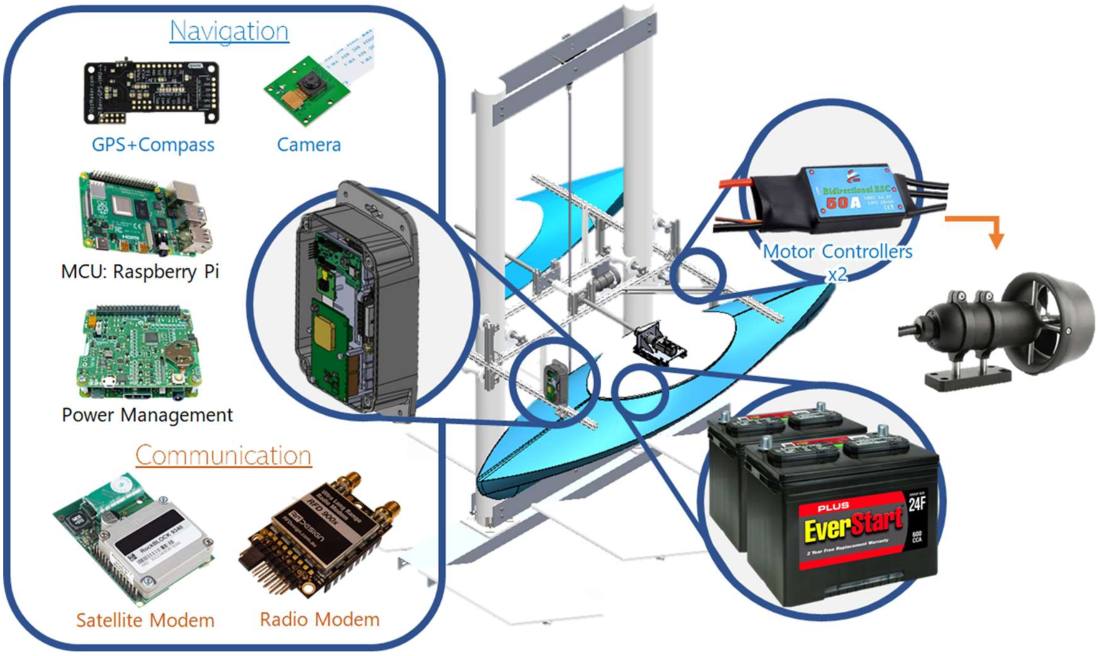

Figure 25: Diagram of notable onboard electronics and their location on/within the robot.

T.6.7.1 Motors

The buoy would be controlled by two motors. The motors themselves would be bidirectional, be able to move forward and reverse, in order to control the robot in a more convenient way. For example, turning the robot would deduce to moving one motor backwards while the other motor propels motors.

In addition, ESC motors were required for the scope of the project to be able to control the speed of the motors. Our program's purpose would be to allow the user to feed these motor inputs thus causing the buoy itself to move in the specified direction.

For the program the main libraries used were pigpio which was for being able to control the Raspberry GPIO as well as time which gave us access to delaying avoiding any potential errors with setting motor speeds too quickly. The program always starts with first arming the motors. This tells the motors to get ready for commands and includes setting the speeds to our stop, maximum and minimum values.

After arming, the ESCs are prepared to receive controls. This may be done through an autonomous navigation system or live through the WebGUI. Whenever a user enters a direction on the WebGUI, a packet is sent from the land base to the robot containing two float values, which determine the speed and direction at which the motors should operate.

T.6.7.2 GPS + Compass & Camera

The GPS navigation could provide position coordinates (longitude and latitude) and Compass gyroscope angle. Since control system read GPS data from the module via I2C, the I2C pins on IMU can be accessed. Raspberry Pi, I2C 3.3v pins could be used to power the module. Also, two SCL and SDA pins should be connected so that the DIsplay Data Channel (DDC interface) can be accessed and allows I2C interface to be used.

For the program, when I2C bus is connected, we could use the addresses of the components on the IMU. Primarily we use the address of 0x42 and 0x6a, which represents GPS and Gyroscope. The python script will first start with set I2C address and begin to read GPS data. This will provide NMEA sentence which contains recommended minimum specific GPS data (GNRMC):

```
$GNRMC,071423.00,A,3254.18201,S,15243.27916,E,0.252,,110721,,,A*72
```

This data string contains latitude and longitude number. The position where character A placed in this string is a Navigation receiver warning which tells whether there is available satellite data exists. If the character is V instead of A, it means the GPS module is not receiving any signals. If the character is A, this tells the python script to continue parse the rest data and give the coordinate information.

T.6.7.3 Power Management:

The Sleepy Pi controls the power to the Raspberry Pi via a switch. When it “decides" that the Raspberry Pi is needed it will switch on the power to the Raspberry Pi and wait for it to boot. The Sleepy Pi has two handshake lines available over the Raspberry Pi GPIO: 24 & 25. Both of them are used for programming the Arduino.

These can be used to coordinate a safe shutdown of the Operating System. Once the Sleepy Pi has detected that the OS is no longer running it will physically cut the power from the Raspberry Pi and go into a low power mode. The Sleepy Pi replicates this type of behavior on the Raspberry Pi. It allows the Raspberry Pi to shut itself down when it’s not being used to save power and wakes it up when it’s got work to do and get back to work.

From the background information about the Car Battery power management, a conventional lead-acid battery in good condition with a full charge should be approximately 12.6 to 12.7 volts. The battery will register approximately 12.3 volts when it has been drained by around 50%. Anything below 11.9 indicates that the battery is dead. The range is narrow, and most people believe that as long as the battery is at 12.0 volts, everything is OK. Based on this, three separate stages have been set up: Power on voltage, Power off voltage, and Force off voltage. By easily controlling the values read from Sleepy Pi, the corresponding threshold has been set to: 23.5 volts, 23.5 volts and 22.5 volts. Depending on the outcomes for the voltage varies, the voltage has been controlled to better manage the power supply from the battery.

T.6.8 Enclosure:

Onboard controllers, sensors, and modems are stored within a waterproof enclosure to protect them against extreme weather conditions during marine operation. We selected an enclosure with an ingress protection (IP) rating of 68, meaning the enclosure can remain watertight while submerged 1.5m. Because our enclosure is ~1m above the robot’s hull, this waterproofness rating is more than sufficient.

T.8 Mechanical Design Analysis and Power Analysis

During the construction of the CAD model the team would check the structural integrity of the design. The wave glider fins were of concern to the team because of their extended arm and load bearing requirements. The max load per fin would be 91 lbs. This is because the maximum breaking force from the generator will create 1100 lbs. 1100 / 12 = ~91 lbs. Simulating the fins it is seen that the fins do not fail and only deflect ~13mm.

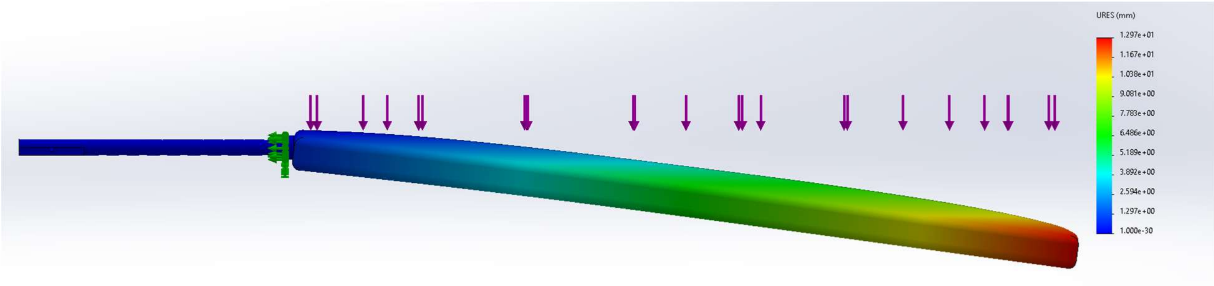

Figure 26: Fin FEA Deflection 91 lb load

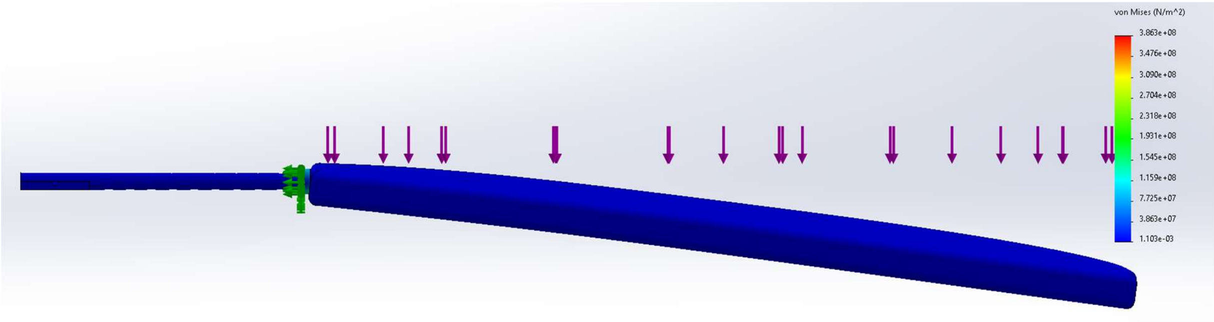

Figure 27: Fin FEA stress 91 lb. load

The next thing the team is interested in was the stresses that would be applied to the spool shaft. This spool shaft will experience a 1100 lb. load. Originally this spool shaft was 1/2-inch diameter with one bearing. The analysis showed that this shaft failed. A second bearing was added for support, but still the stress was greater than the yield stress of the material. Finally, the diameter was increased to one inch. This proved to have approximately an order of magnitude less stress than yield. These analyses can be seen in Figure through Figure respectively.

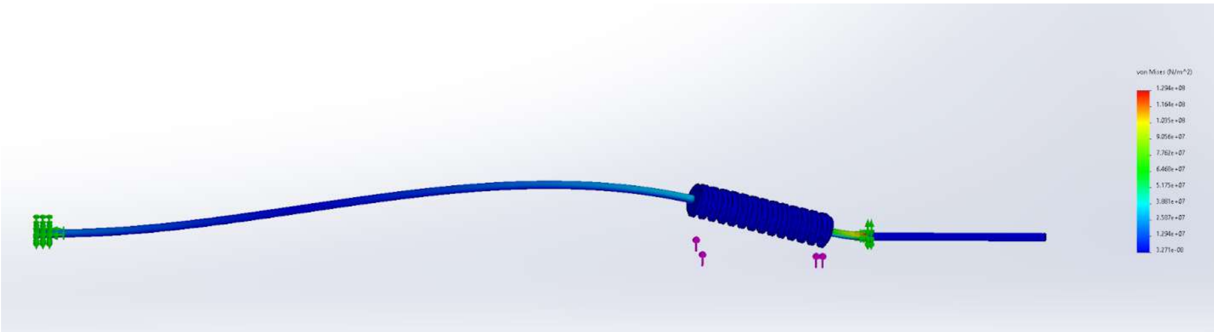

Figure 28: Spool Shaft FEA 1/2 in 1 bearing

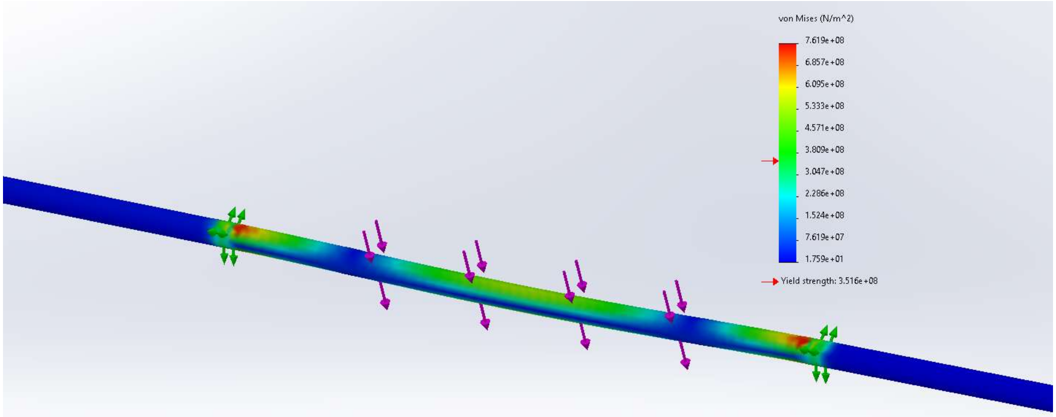

Figure 29: Spool Shaft FEA 1/2in 2 bearings

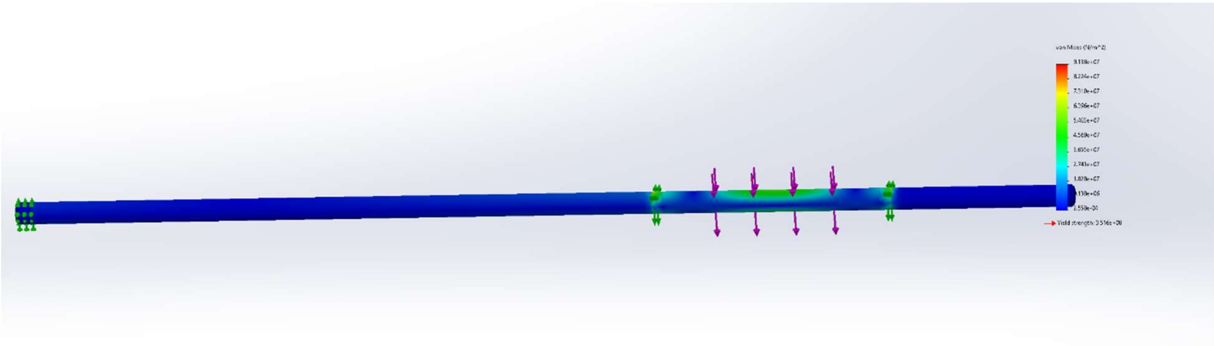

Figure 30: Spool Shaft FEA 1 in 2 bearings

This shaft can now support the load, but it must be proven that the shaft supports can also take the load that will be experienced. A simulation, shown in Figure 31, shows that the supports have a factor of safety of approximately 2.

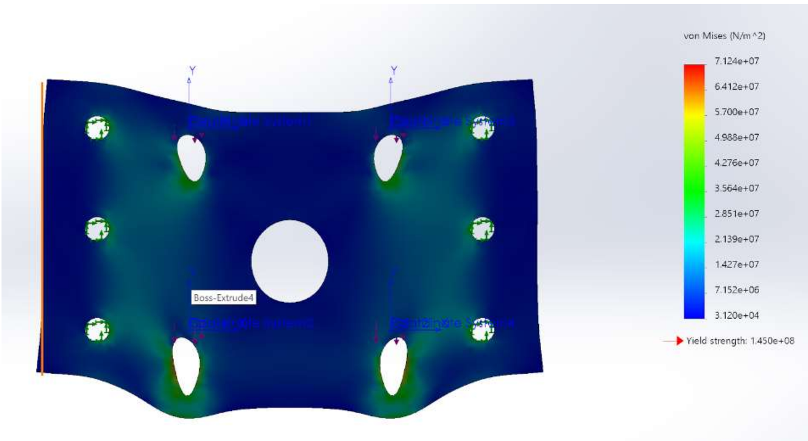

Figure 31: Shaft Support FEA 1100 lb. load

Lastly, the heave frame was analyzed in two modes of forcing. The first is 1100 lbs. pulling in on each of the middle bolts between the aluminum plates on the top and bottom. This simulates the maximum load from the cable. The second analysis was a 220 lb. load across the bottom of the heave frame to simulate thrust from the wave glider. The aluminum plates and ½” bolts had their lowest factors of safety (3.1 and 1.5 respectively) during the 1100 lb. buckling force. Stress plots of these parts are shown in Figure 32 and Figure 33. The lowest factor of safety for the brackets and PVC pipes (2.9 and 7.3 respectively) was during the thrusting. Stress plots of these four parts are shows in Figure 34 and Figure 35.

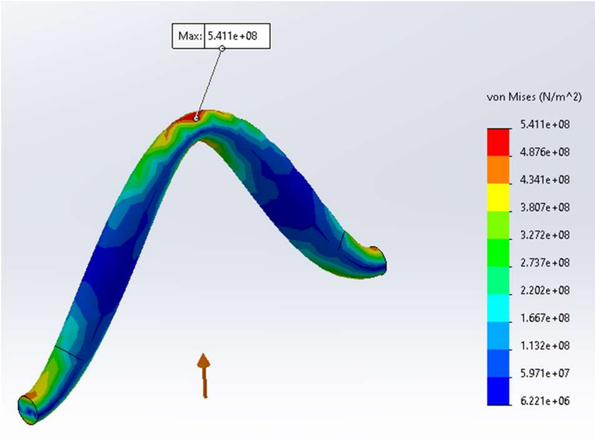

Figure 32. 1/2" Bolt under buckling

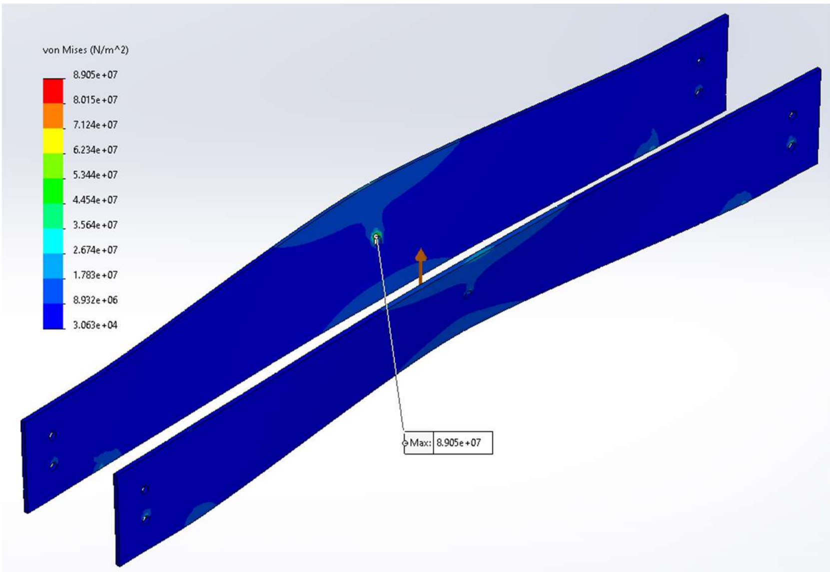

Figure 33. Aluminum plates under buckling

One point of interest the team wanted to look at was the resistance of the heave plate to vertical motion. The flow analysis is promising. It shows that there is a very large resistance to heave motion. The max force of 1100 lb. is achieved at 0.7 m/s of vertical heave. This will not be the normal operating condition of the heave plate, but it is promising to see that there is such a large heave force at slow speeds.

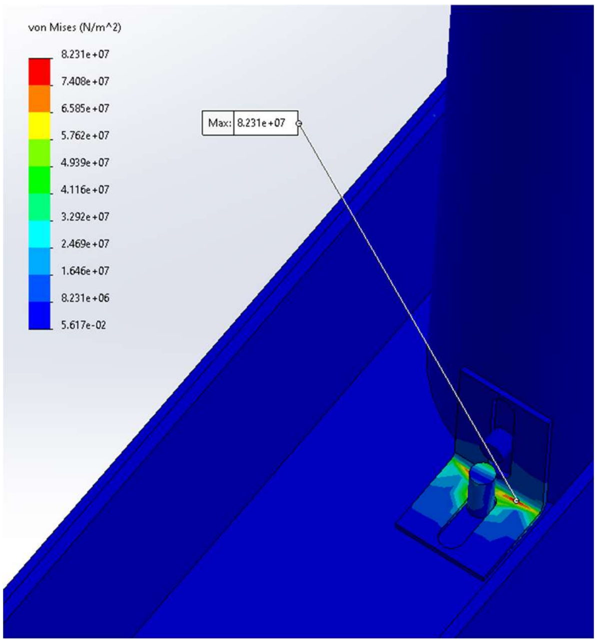

Figure 34. L Bracket under thrusting

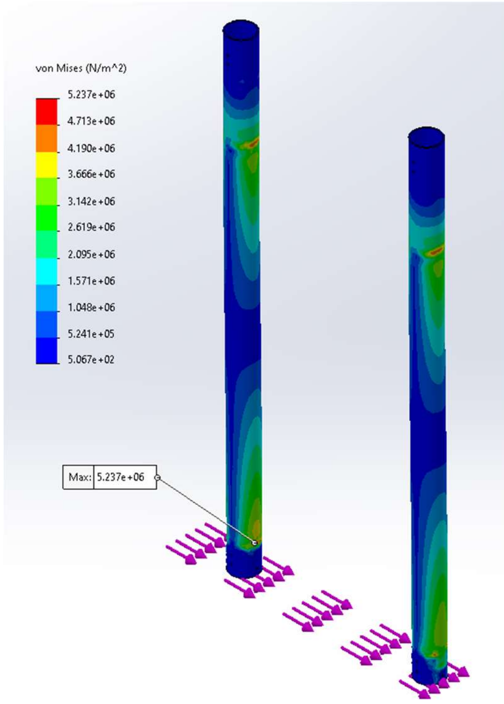

Figure 35. PVC Pipes under thrusting

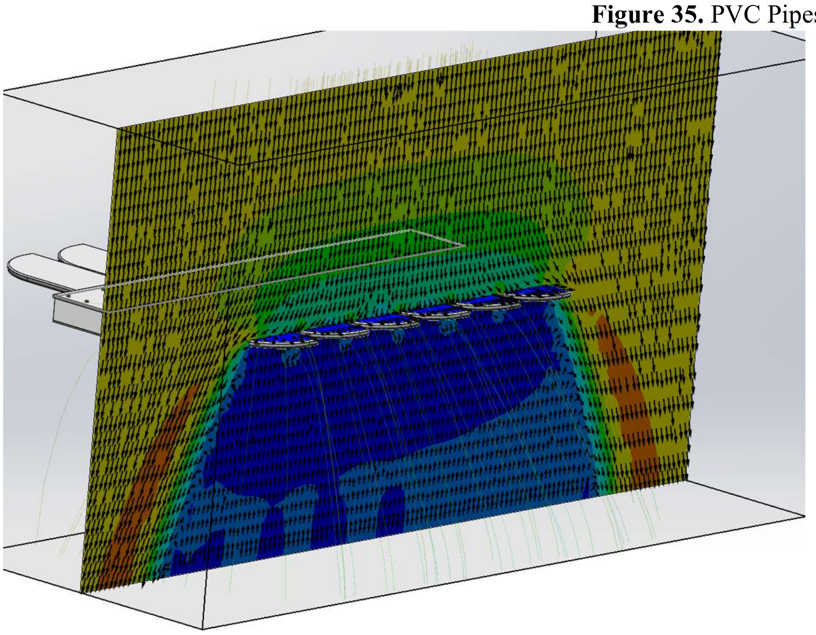

Figure 36: Wave Glider Flow in Heave Configuration

The flow simulations also shows that when the wave glider is in propulsion configuration, meaning the fins are unlocked, then it is able to divert water and generate a thrust. According to the simulation the thrust is about 80 lb. (360 N) of thrust at 0.7 m/s heave velocity. This is very promising for the team because it is expected to be able to achieve that heave velocity on heavy seas.

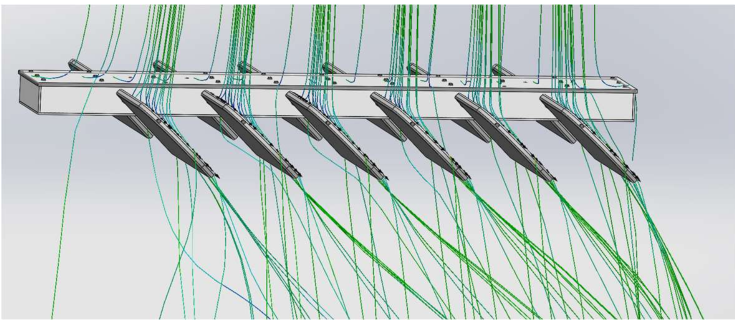

Figure 37: Wave Glider Propulsion Configuration

Overall, the wave glider shows promising signs of effectiveness but there will need to be more analysis performed. The main concern the team and advisors have for the system is the dynamic response of the coupled vibrational system. It is easy to study the parts independently, but the complexity increases when trying to make an accurate dynamic model and simulate it. The team created a dynamic model as seen in Figure 38 and an accompanying simulation over winter break with the help of a few grad students. This model was used to confirm that the heave plate was the appropriate size and observe the difference in power generation when the heave plate is placed at varying depths. The resulting simulation showed a potential peak power generation of up to 350 watts. In addition, it showed that there is no significant power gain from pushing the heave plate further down.

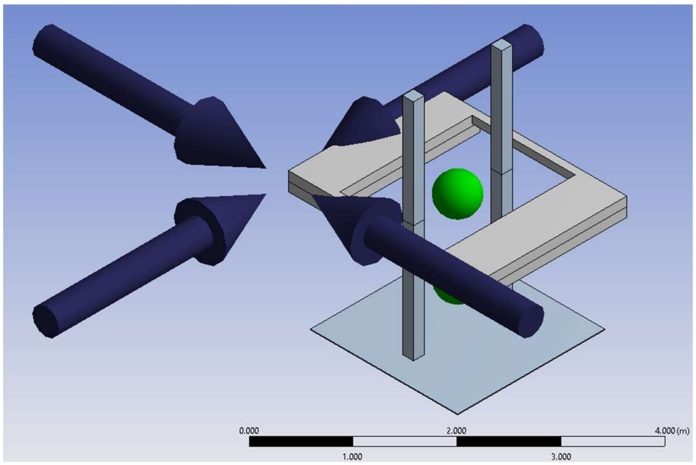

Figure 38. ANSYS simulation of the two-body system

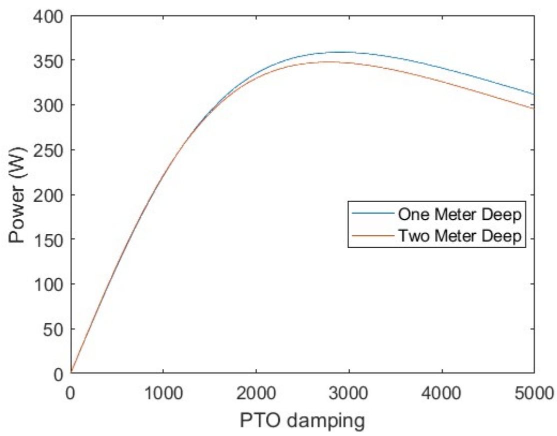

Figure 39. MATLAB plot from ANSYS simulation

T.9 Conclusion

The work for this project has encompassed every step in getting a product through its life cycle. Last semester the team defined the problem, developed customer needs, generated concepts to satisfy customer needs, prototyped and analyzed those concepts, down selected to a single concept, planned testing and validation of engineering specifications, created a detailed CAD, and performed FEA and hydrodynamic analysis. This semester the team manufactured, assembled, and validated the device. The validation test was performed at Claytor Lake where the team effectively verified all the important specifications such as speed, movement efficiency, water tightness, power generation, and stability. It was determined that the design requires a few adjustments, such as, more water tightening, but the important specifications were achieved. The constructed device meets and exceeds the specifications that make it a desirable product for customers. For the team, this means the overall project was a success. There are also multiple systems in the device that are exciting new solutions to the energy harvesting problem. This allowed the device to be simpler and more effective than previous designs. These novel solutions include the helical spool power take off and the variable fin angle wave glider. Because of the promising outlook of these solutions, they will be explored more in the future by researchers in the field. Overall, the team learned that the concept and general design is sound. There will be more work needed to create sturdier watertight hulls as well as improve the adjustable fin wave glider mechanism. The team believes that these modifications are easily achievable and in doing so will create a commercially ready product. The team is happy with their work and achievements they accomplished. They look forward to the future of their device and are excited to see what is possible.

Build and Test Report

BT.1 Prototype Overview:

BT.1.1 Test Objective

The main objective of this project is to develop a wave energy harvesting device capable of storing the generated power and using it for external applications. This wave energy converter (WEC) will primarily be used to power systems of external entities such as fish farming operations, unmanned vehicles or autonomous robots. In addition to these capabilities the device itself can be equipped with a user customizable suit of sensor arrays for ocean observation and meteorological purposes. In order to ensure that the OWPAB would be able to achieve these goals a set of tests were conducted based on the customer needs discussed in section T.2 and seen in Tables 2 and 3.

The tests were conducted in 3 sections. The ME team at Virginia Tech focused on testing a full-scale prototype seen in figure 40, while the ME team at Stevens university focused on small scale wave tank testing (figure 41). Data from both tests would be then used in ensuring each consumer need was met and if not understanding what went wrong. The ECE team at Virginia Tech would be running tests on the OWPAB in parallel to the ME team and testing out a different set of variables.

Figure 40: Full Scale Testing in Claytor Lake

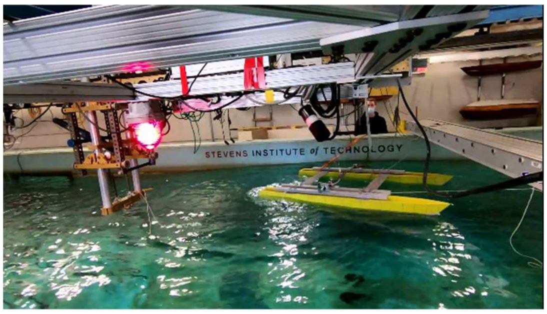

Figure 41: Scale model wave tank testing

BT.2 ME Validation Test Plans and Results

Engineering experiments are used to perform any test for an engineering design, and it gives an approach to the scientific method. The aspects of the validation plans can be divided into four components which are introduction, validation approach, schedule, and reference documents. The introduction should include the people that relate to the testing, purpose of validation plan, and explanation and description of the product. The validation approach uses strategy for testing and gives resource requirements for detailed test procedure. The validation schedule gives a specific plan time of the testing and analysis of the data. The reference documents show the origin of the information of testing like journal articles, websites, and SMEs. The validation plans below outline the process the team will use to quantify whether the target specifications were met. There are 20 validation plans for the 20 target specifications the team has set. Each validation plan describes the reason why the test must be performed as well as the overall explanation of the validation approach. Each plan has a step-by-step outline of the process that it entails, the resources required to perform the test, safety precautions that need to be considered, and an explanation of the data collection methods. Figure 42 shows an example of the step-by-step instructions for collecting data.

- Steps to Follow
    - i. Charge the battery to full capacity using the charger
    - ii. Use the battery tester to test: capacity, charge rate, discharge rate and discharge rate under load.
    - iii. Collect data for multiple battery cycles (at least 200).
        - a. *Note –One cycle is defined as a full drain and recharge.
    - iv. Follow steps outlined in Agarwal, Uthaichana, DeCarlo, and Tsoukalas's paper for data collection.
    - v. Create battery models as described.
    - vi. Use MATLAB or Excel to process data and compare to models.

Figure 42. Step-by-step instructions for TS-01: Battery Capacity

Each test was performed with measuring equipment to collect data. The summary for the equipment used and the final results of each validation test can be seen in **Table 6**. **Appendix A** shows detailed test plans for each specification. Overall, the team was only able to meet 65% of the marginal values during testing. This is primarily because the team set unreasonable goals during the design process last semester and not due to a failure of the prototype. For example, the team set the target specification for buoyant force based on the maximum weight of the entire prototype. We successfully met the weight target by keeping the total weight to just 298 kg, but this led to a lack of buoyant force, and we failed to meet the marginal target value of 10,000 N. However, this does not mean that the prototype is vulnerable to capsizing under heavy waves. Rather, the team should have based the marginal value for the buoyant force on the total weight of the system instead of picking an arbitrary target value.

Table 6
Target Specification Table with Measurement Devices

Target Specifications Table							
Customer Need #s	**Eng. Characteristic**	**Rank**	**Units**	**Marginal Value**	**Ideal Value**	**Verification Measurement Device**	**Meets Target Value?**
2, 5, 8, 9, 10, 11, 12, 16, 17	Battery Capacity	**1**	kWh	2	10	Battery Tester	Passed – 2.4 kWh installed
5, 7, 9, 10, 11, 12, 14, 17	Payload Mountable Area	**5**	m^3	4	6	Measuring tape	Failed – 1.27 m^3
3, 4, 6, 8, 11, 17	Bounding Volume	**14**	m^3	25	18	Measuring tape	Failed – 27 m^3
2, 6, 14	Maximum Harvestable Wave Amplitude	**16**	m	2	5	Measuring tape	Passed – 2.1 m
3, 4, 8, 9, 14, 17	Weight	**18**	kg	1000	500	Scale	Passed – 298 kg

1, 2, 5, 6, 7, 11, 14, 15, 17	Structural Integrity	**2**	FOS	4	9	FEA Analysis	Failed – 2.7
6, 8, 9, 11, 17	Max Customer Added Load	**9**	kg	50	detaeil200	FEA Analysis	Passed – 79 kg
6, 8, 11, 15, 17	Buoyant Force	**11**	N	10,000	20,000	Volumetric Analysis	Failed – 8810 N
9, 16	Cost	**12**	$	$250,000	$100,000	BOM	Passed - $6124.32
1, 2, 15	Service Life	**13**	Years	1	5	Component Specifications	Passed – 4.5 Years (bearing life)
2, 5, 9, 12, 14, 16	Charge Time	**7**	Hr	23	12	Average Energy Calculation	Failed – 150 hrs @ 16 W
1, 2, 6, 7, 8, 11, 12, 14, 15, 17	Water Resistance	**3**	IP rating	7	8	Submersion tank	Failed – Water let in
1, 2, 6, 8, 15	Roll Angle	**8**	Degrees	30	90	Protractor + Pendulum	Passed – Unable to be rolled
1, 6, 15	Head on Impact with Rigid Object	**10**	J	3-5	6-7	Force Gauge	Unable to test
2, 5, 8, 9, 11, 12, 16, 17	Movement Efficiency	**15**	km/kWh	0.5	1	Open Body of Water	Passed – 20.125 km/kWh
3, 4, 7, 9, 15, 16	Deployment time	**19**	Min	20	10	Stopwatch	Passed – 5 min
13	Operating Nosie	**20**	dB	100	50	Decibel meter or iPhone	Passed – Avg. 60-80 dB
2, 7, 9, 12, 14, 16	Average Energy Generated	**4**	W	10	100	Energy Measuring Circuit	Passed – 16 W
1, 2, 6, 9, 14, 16, 17	Natural Frequency	**6**	Hz	0.25-1	0.1-2	Wave Tank	Passed – 0.236 Hz
2, 7, 8, 13	Max Speed	**17**	Kts	3-5	6-7	GPS + Stopwatch	Passed – 3.04 kts

BT.2.1 Power Output Results

The team tested the full-scale prototype on Claytor Lake near Virginia Tech. Due to limitations on the body of water available the size and scale of the waves on the lake were not ideal for testing power generation as the device has been designed to operate in an ocean swell. However, we were able to create singular large waves by driving a motorboat at speed past the OWPAB to test the power output. As seen in figure 43, the peak voltage generated was around 3.5 volts. This translates to a power output of approximately 50 watts. However due to the limitations of the setup used, the team believes that there is significant loss between actual generation and measurement because of inefficiency of the 3-bridge rectifier and impedance matched resistor used. It was estimated that the rectifier was costing the team anywhere from 20-30 watts in heat output. Taking this into account, the team estimates peak power output to be between 80-90 watts. The results from the 0.5 scale testing conducted at Stevens university also showed promising results scaled down (figure 44).

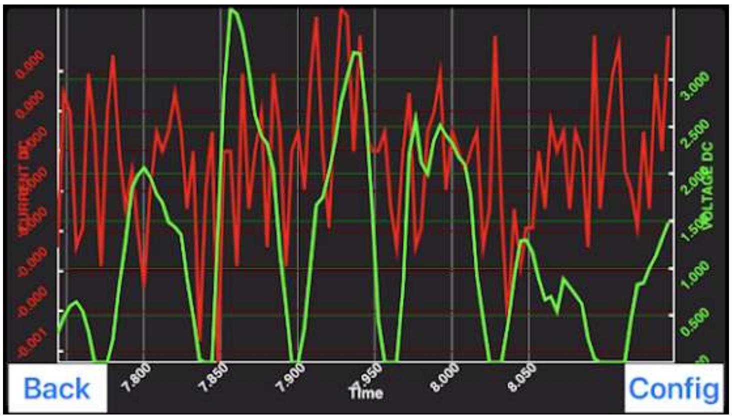

Figure 43: Peak voltage output from Claytor Lake test

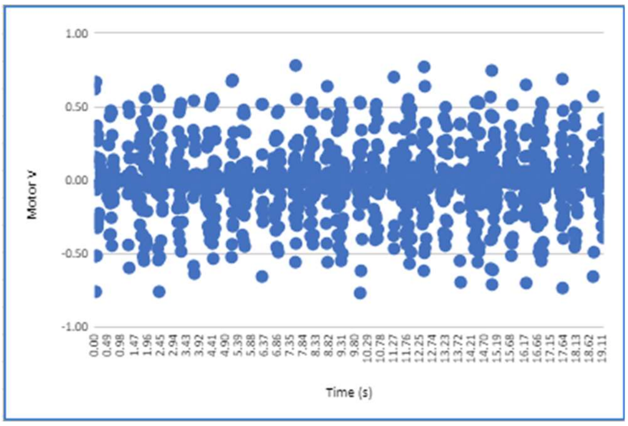

Figure 44: Scale model wave tank results

BT.3 ECE Build and Test

Early prototyping began in November 2021, where our team constructed a mock-up of a RaspberryPi communicating over I^2C with a ‘satellite modem’ to send and receive messages from our WebGUI. Because we didn’t have access to an actual Iridium SBD modem, we instead programmed an Arduino with WiFi capabilities to interact with the WebGUI through HTTP, in essence acting as both the Iridium gateway server *and* the modem.

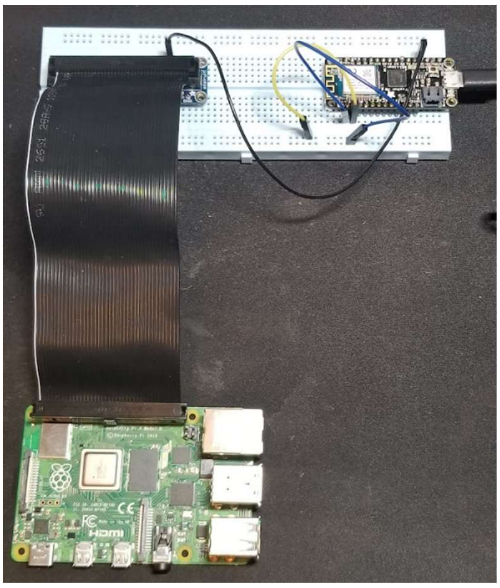

Figure 44: Early prototype to demonstrate communication over a faux Iridium SBD channel

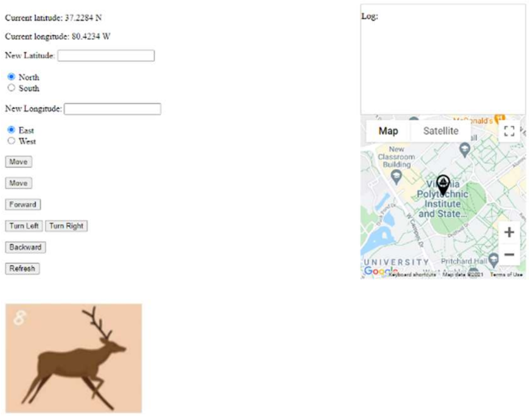

Figure 45: Early iteration of our WebGUI. Used Google Maps API and displayed a GIF as a stand-in for a live video feed.

In December 2021, the team began fleshing out how sensor data would be collected. We successfully obtained GPS information and could record video. The WebGUI was also designed to show GPS data using text and Google Maps. It was able to show sample video feed at 1 fps using images that were hard coded in and it contained control buttons that printed out messages when pressed.

Low-level testing of our Radio modem began in January 2022, where we could transmit simple, UTF-8 encoded messages. During this stage, we observed noise that sometimes prevented the message from being properly decoded; this prompted the development of our communication system with reliable data transmission.

By February, we had a rough version of our reliable communication system, which we used to compare MJPEG and H264 live video encoding over our link. During this stage, the WebGUI was also updated so that there are buttons to change what type of motor is being used and that allows the user to tell the robot to stop. Integration of the communication system with the land base was started in this stage so that the robot and land base can send and receive messages between each other.

In March, we began our first steps towards robot integration. We confirmed our SleepyPi v2 could safely maintain 5V to power our electronics and programmed ESCs for locomotion. We had also begun testing our radio link’s speed during this stage. The WebGUI and communication system was completed in this stage and the communication between the robot and land base was able to be verified. Styling was also added to the WebGUI so that it was more visually appealing to the user.

Integration was complete in April when our interdisciplinary team conducted live control testing in McComas Pool and Claytor Lake (see Section 3.1 for more details). We also received our satellite so integration of that into the communication system was started. The land base was able to communicate with the modem using email to send packets.

3.1 ECE Testing

3.1.1 Radio Testbench

Formalized testing of our communication system started in March with a set of testbenches specially written to assess the speed of our radio link with the overhead of our comm. system.

The first test was a packet loss test. This test involved sending packets of various length unreliably over radio. These packets still were enclosed in a datagram, as to validate data integrity with a checksum.

The second testbench tested the link's throughput. The testbench involved sending a large batch of data using packets of various length, then observing the amount of time it takes to send the batch of data. We expect that as packet length increases, the relative data overhead introduced by our comm. system decreases. As expected, when the packet length increases, so too does the throughput, reaching a maximum 4800 Bytes per second at a packet length of 4096 Bytes.

The last test was a latency test, which measures the round trip time (RTT) of sending packets of various lengths and receiving their corresponding echoes. We observed an average RTT latency of 4.35 seconds - greater than we had anticipated.

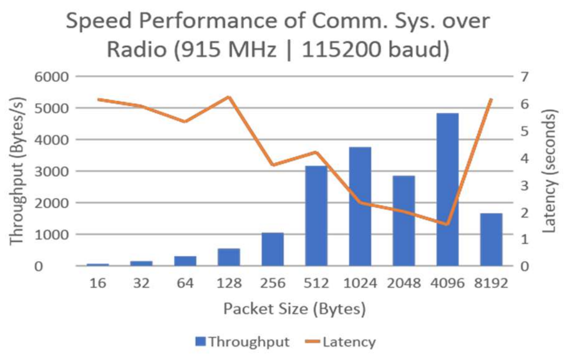

Figure 46: Results from our radio speed testbenches, measuring throughput and latency at various packet sizes.

Based on our later findings during live control testing these test benches were repeated outdoors.

3.1.2 McComas Pool and Claytor Lake Live Control

To validate our live control scheme in a real demonstration, our interdisciplinary team operated our robot in McComas pool on 04/08 and Claytor Lake on 04/11. We were able to control the robot with surprising finesse despite our early radio testbench results. The delay between when an operator pushed a button and when the robot was observed moving was oftentimes under 1 second. Live video struggled in the indoor McComas pool; by the end of our hour-long test time, the live video fell ~20 seconds behind. However, this discrepancy was reduced significantly outdoors under similar operation times, often < 5 seconds. We expect the difference is due to radio signals echoing when indoors, causing noise. We believe with improved H264 keyframe scheduling, the observed delay in the live video can be further reduced.

Atop of these qualitative observations, we used our heartbeat behavior to obtain RTT latency when outdoors. We observed a greatly reduced latency with an average heartbeat response time of 0.8 seconds. We were also able to maintain a radio connection for one mile before line of sight was broken.

3.1.3 Power Management Tests

Using a DC power supply, we could set the voltage and directly observe the current our system consumes across its different states

Table 7

Tabulated results from power management testing

State	Description	Voltage	Average Current	Power
Idle	All electronics powered. No data being transmitted / received. No motors being driven.	25.2 V	0.188 A	4.73 W
Low-Power	Only SleepyPi and ESCs are on. SleepyPi performs occasional voltage checks.	9 V	4 mA	36 mW
Live-Video	All electronics powered. Radio sends 4 H264 frames every second.	25.2 V	*0.271 A*	*6*.83 W
Live-Control + Motor Full-Power	All electronics powered. Radio sending live video and motors are driven at full power.	25.2	2.38 A	59.63 W

3.1.4 ECE Test results

Table 8

Tabulated results of tested deliverables against target specifications

Characteristic	Marginal Value	Ideal Value	Delivered Value
High-Speed Data Throughput	625 Bps	625 kBps	5 kBps
Message Reliability	10%	0%	Reliable TX - 0% (assuming link is eventually reestablished if ever down) Unreliable TX - 12.4% (for packets at or under 4096 Bytes)
High-Speed Transmission Latency (One-way)	3000 ms	100 ms	1163 ms
Low-Speed Transmission Latency (One-way)	60 s	600 ms	~10 s *(from testing w/ another satellite modem, 9603N).*
High-Speed Transmission Range	3 km (originally 0.5 km)	8 km	1.6 km *(from informal range test)*
Low-Speed Transmission Range	Global	Global	Global
Low Power Consumption	2.5 W	0.5 W	36 mW
Idle Power Consumption	15 W	2.5 W	4.73 W
Peak Power Consumption	260 W	130 W	59.6 W
Waterproofness	IP 66	IP 68	IP 68
Cost	$4,250	$1,000	$963.71
User Interface Clarity	7	10	9

BT.4 Challenges and Limitations

One of the challenges that our team faced was getting all of the materials and parts we needed on time. Due to mismanagement of our orders, we didn't receive our satellite modem until mid-April. We were able to borrow a similar modem to become familiar with the devices interface, but could only do so through an Arduino, thus limiting the time we had to work with it in conjunction with our communication system.

Since this was an interdisciplinary project, our team was able to work closely with the Mechanical Engineering team to make sure our product was delivered successfully. This allowed us to learn how to communicate our requirements to another team. Although it was initially a challenge to define how our system would interface with the ME's project and vice versa, it gave us invaluable insight into how to structure and manage interdisciplinary teams in parallel and how to communicate ideas effectively at a high-level.

During prototyping we encountered two instances where our hardware broke. First, our Raspberry Pi camera over winter break - likely due to exposure to an external static charge. When working with our reordered camera, we took measures to discharge our hands when working and encased the camera during storage. Another component failure was our GPS module. When testing it with our GPS antenna, we observed smoke and the component became non-responsive.

Similarly, there were instances where the ME hardware that was ordered was simply wrong. The team had to learn the hard way the importance of tolerancing a part properly and gained a valuable insight into the difficulties of building a complex project from scratch.

BT.5 Future Steps

Satellite control: Our team was unable to successfully test the satellite modem receiving and sending packets. Software was created to send packets to the satellite via email and also read emails from and email specified from the iridium service. In order to validate this, the satellite needs to be connected and be able to get a signal.

Wave glider: The team believes that the current waveglider needs to be redesigned in order to allow for infinite angle control. This would additionally be supplemented by a sensor suit that would be capable of predicting the optimal angle lock for an upcoming wave. The machine learning based algorithms needed to operate such a system would be a real challenge.

Power electronics: The team did not focus much on how generated power will be transferred to the storage medium. The power management electronics such as charge controllers and distributors will need to be a key focus in the future now that it is clear that power can be generated through this device. This will allow the device to properly interface with the client devices such as fish farm operations and auxiliary autonomous robotics.

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Appendix A:

Full Validation Plan

TS-01: Battery Capacity

Validation Approach

Strategy

- The batteries and charging systems being used will need to be validated to ensure that generated power is being adequately stored. The battery capacity and charge rates will be tested to listed spec. Using the steps and procedures outlined in Agarwal, Uthaichana, DeCarlo, and Tsoukalas's paper on the "Development and Validation of a Battery Model Useful for Discharging and Charging Power Control and Lifetime Estimation."

Resource Requirements:

- Battery tester
- Computer
- Ideal energy source
- Battery Charger
- Voltage Load|

Detailed Test Procedures:

- Steps to Follow
  i. Charge the battery to full capacity using the charger
  ii. Use the battery tester to test: capacity, charge rate, discharge rate and discharge rate under load.
  iii. Collect data for multiple battery cycles (at least 200).
    a. *Note –One cycle is defined as a full drain and recharge.
  iv. Follow steps outlined in Agarwal, Uthaichana, DeCarlo, and Tsoukalas's paper for data collection.
  v. Create battery models as described.
  vi. Use MATLAB or Excel to process data and compare to models.
- Explanation of Data Collection Methods
  i. Multiple charge cycles are required to get a true estimate of the battery's charge retention and charging rate.
  ii. MATLAB is the best large dataset processing tool available. It is especially useful in creating the linearized models real world data will be compared against.
  iii. Development of partially linearized (control orientated) models is critical in predicting the lifetime estimation of the battery.
- Required Safety Precautions
  i. **PPE is REQUIRED** in case of a battery chemical leak or fire.
  ii. Testing should be conducted in a **dry, temperature-controlled environment.**
  iii. **CO2 fire extinguishers** are advised due to potential of lithium-ion based fires.
  iv. **Safety grounding is REQUIRED** due to potential of short circuit and high voltage/current.
  v. No ear or eye protection required.
  vi. Voltage regulators for charging banks recommended.

Reference Documents:

- Development and Validation of a Battery Model Useful for Discharging and Charging Power Control and Lifetime Estimation
- Validation and benchmark methods for battery management system functionalities: State of charge estimation algorithms
- (More will be added as specific parts are chosen)

References:

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TS-02: Structural Integrity

Validation Approach

Strategy:

- The structural integrity of the boat is incredibly important. Structural integrity refers to having sufficient factors of safety for the mechanical behavior of materials. The mechanical behaviors generally to be concerned with are yield failure, fracture failure, buckling, and cyclic loading. It is important to study these so that in operation, the applied loads, moments, and stresses do not cause failure in any component. The factor of safety defined by our specifications allow room for greater stresses than anticipated to occur without leading to failure. Every component on the boat will experience some sort of stress. For this validation, the focus will be on only critical components prone to certain failures. The components to be considered are buckling in the masts, yield/fracture in the mast rollers, bending in the H-frame, and yield/deflection of the glider fins.

Resource requirements:

- Access to data tables for material properties.
- A calculator will be required for hand calculating operational loads and moments.
- Access to SOLIDWORKS 2021 with simulation for FEA analysis of each of the components defined in the strategy.
- Completed sub-assembly models to have FEA done on. FEA is not done on the entire boat assembly, but rather just on specific important sub-assemblies.

Detailed Test Procedures:

- Steps to follow:
  i. With hand calculations, analyze and determine what loads and moments will occur on the component sub-assembly.
  ii. Launch SOLIDWORKS 2021.
  iii. Load the desired sub-assembly.
  iv. Enter the SOLIDWORKS Simulation add-on and create no study (buckling study for the mast and static for the others).
  v. Select the correct material. If such material is not in the SOLIDWORKS database, reference online sources and create a custom material with the correct material properties.
  vi. Apply all necessary boundary conditions to accurately constrain the component sub-assembly.
  vii. Apply all loads as calculated in the first step, ensuring correct magnitude and direction.
  viii. Use the connections menu to define the surface to surface contacts within the subassembly.
  ix. Create mesh using linear strain triangles, designated by element type "HIGH".
  x. Create the mesh and run the simulation.
  xi. Document critical stress values.
  xii. Make the mesh finer, run the study, and record critical values once again. Repeat till results converge within 3%.
  xiii. For buckling, compare the critical load from the FEA results to the applied load to verify the factor of safety meets specifications. For the others, use the FEA von mises stress to compare with the yield strength of the material to ensure the factor of safety meets specifications.
  xiv. Repeat the process for all of the following component subassemblies: buckling in the masts, yield/fracture in the mast rollers, bending in the H-frame, and yield/deflection of the glider fins.
- Explanation of Data Collection Methods
  i. Using strain gauges or other measurement devices to capture actual stresses or deflections in operation is unrealistic. The ability to accurately capture them would be expensive and time consuming. FEA is a great way to get accurate results. Using SOLIDWORKS simulation allows the determination of operational stresses to ensure factors of safety are met. Because the accuracy depends on proper meshing, the procedure states that the mesh must be refined until a 3% convergence is met. This ensures the results are accurate. The critical component subassemblies to have FEA performed were chosen because they will receive the majority of the loads and will be most prone to failure.
- Required Safety Precautions:
  i. The safety requirements for this test are all bound by safe usage of a computer. This includes maintaining a comfortable wrist position as well as looking away from the screen for 30 seconds every handful of minutes to reduce eye strain.

TS-03: Water Resistance

Validation Approach

Strategy:

- Testing water resistance for the boat is important to ensure electrical components will be safe. In addition, buildup of water inside the hull would eventually lead to the boat sinking. An IP rating of IPx7 will ensure the hull will be able to be submersible in 1m of water for 30 minutes. Although the hull will not be submerged in water, having a rating of IPx7 will let the team know that the hull is watertight.

Resource requirements:

- Submersion tank capable of holding hull 1 meter deep
- Weights to hold down boat hull in water
- Straps
- Stopwatch

Detailed Test Procedures:

- Steps to follow:
  i. Secure one end of straps to weights.
  ii. Secure other end of straps to the H-frame of the kayak.
  iii. Fill submersion tank with water.
  iv. Hold hull in tank for 30 minutes.
  v. Drain tank.
  vi. Inspect boat hull for water ingress.
- Explanation of Data Collection Methods
  i. The seals and joints of the hull will be outlined in an excel sheet.
  ii. After submersion for 30 minutes, an inspector will go through the list of seals in the excel sheet and check for water ingress.
  iii. A pass of fail will be recorded on the excel sheet depending on if water has seeped into the hull.
- Required Safety Precautions:
  i. When the handler is securing the weights, they must be careful to not drop weights on feet.
  ii. Safety goggles should be worn in case that straps break.

TS-04: Average Energy Generated

Validation Approach

Strategy:

- This plan outlines the validation approach to Team 43 Wave Powered Robot's Average Energy Generated. This specification is important to the team because it will determine how effective the design is at harvesting ocean energy, a main concern for the project. The team needs to prove that the design meets the requirements for success that was set in the beginning of the semester. If the design does not meet the specifications, then the performance and marketability of the device will be severely impacted.
- To do this the team will be using the scale prototype constructed by Stevens university. It was coordinated that Stevens University would build a scale model of our device and use it to preform tank testing on. The full-scale device will be to large to fit in the tank. A systematically similar device will be constructed and tested in the Stevens tank. The device will be outputting power when the wave tank is turned on and this will allow us to extrapolate the number to the full-scale device. This number will need to have a scaling factor that has already been found by the research in the CEHMS Lab.

Resource requirements:

- Functional Sub-Scale Device Constructed by Stevens
- Stevens Wave tank and all certified operating personnel
- Available timeslots at the wave tank
- Energy measuring circuit. Most likely a current shunt, but it is up to Stevens university's discretion
- Data logging device. Most likely a data logging voltmeter such as an oscilloscope

Detailed Test Procedures:

- Steps to follow:
  i. Power on functional sub-scale model and preform dry functional test
  ii. Place sub-scale in the wave tank and start the data logging
  iii. Enable wave generation and sweep through a range of periods and amplitudes
  iv. Disable wave motion
  v. Turn off data logging
  vi. Remove sub-scale from tank
  vii. Import data into data processor
  viii. Correlate energy generated to different wave types
  ix. Calculate the average power for the whole data set excluding downtime and setup time
  x. Determine subscale average power generated
  xi. Scale calculated average power generated to the full-scale with scaling factor
  xii. Determine if the specification meets criteria
- Explanation of Data Collection Methods
  i. The sub-scale prototype will probably not have onboard energy conversion to battery system. Most likely it will have a cable that sends power to an external power monitoring system. This means that it would be possible to use a commercial off the shelf data logging system and thus reducing the scope for stevens university. The team would most likely use an oscilloscope and a large shunt resistor to determine power.
  ii. The team would benefit from having multiple wave scenarios tested, including changing the period and amplitude of the waves. This would simulate different conditions on the ocean and shows how the device would perform. We could even extrapolate the average ocean conditions for different locations and calculate how much power we would generate on average for a given location. This could be a good figure to use when marketing to customers.
- Required Safety Precautions:
  i. Stevens University owns the wave tank, and they have their own set of safety precautions to use when operating the wave tank. I will touch on a few that may be relevant
  ii. The large body of water poses a drowning hazard especially when the wave tank is enabled. Members in the vicinity should be comfortable with swimming
  iii. The wave tank has large moving plates that could be a crushing hazard
  iv. The sub-scale model will have pinching points. This will need to be considered when handling.
  v. The Device will also be generating electricity near potentially conductive water. Electrical safety will need to be taken into consideration because of the increased shock hazard
  vi. There most likely will be no batteries on this device but it is possible that there may be some. Lithium battery safety procedures will need to be followed if that is the case

TS-05: Payload Mountable Area

Validation Approach

Strategy:

- Payload mountable area is another important specification for our boat. We want to make sure that the customer has plenty of room to mount additional batteries, solar panels, monitoring equipment, cameras, or whatever they intend to mount on our boat for their use. The H-frame, which is the frame structure that sits atop the two hulls parallel to the water, will be constructed with 80/20. The customer will be able to use standard 80/20 brackets and mounting equipment to install their components to the boat. Customers can even add additional pieces of 80/20 to the mountable area as needed.

Resource requirements:

- Complete assembled product to measure.
- Calculator to calculate area.
- A tape measurer for distance measurements.

Detailed Test Procedures:

- Steps to follow:
  i. Approach boat with tape measurer in hand for distance measurements.
  ii. Measure and record the mountable area length. This is the distance from the H-frame cross bars, which are the members perpendicular to the kayak length, at the front and end of the kayaks.
  iii. Then, measure and record the mountable area width. This is the distance from the edge of the vertical 80/20 that holds the rollers to the kayak end of the 80/20 perpendicular to the kayak length.
  iv. Multiply the length by the width to get an area.
  v. Since the width only covers the area on one side/half of the masts, multiply that area by two to get the entire mountable area.
- Explanation of Data Collection Methods
  i. Using a tape measurer is by far the best way to measure distances for the areas. These areas do not be incredibly precise. This procedure measures one side of the mountable area first and doubles it to get the total. The H-frame is symmetrical so this should be accurate. No measurement repetitions are needed as one is not likely to read a tape measurer measurement to be different on multiple occasions of the same distance.
- Required Safety Precautions:
  i. This test requires interaction with the boat. As the boat may weigh up to 500 pounds, it is important that the boat is firmly and sturdily set on the ground when measuring. The boat should be tied down with straps to ensure no shifting of the heavy boat occurs. This could be a pinch or crush hazard.

TS-06: Natural Frequency

Validation Approach

Strategy:

- The natural frequency of the boat is critical to maximizing the amount of energy that can be extracted from ocean waves. To test the natural frequency of the boat, it will be exposed to incrementally increasing wave periods in a wave tank.
- The wave period that results in the most power generated by the energy harvester will most closely resemble the natural frequency of the boat itself.

Resource requirements:

- Wave tank
- Boat

Detailed Test Procedures:

- Steps to follow:
  i. Secure the boat in the middle of the wave tank such that it cannot move but energy harvesting is not affected.
  ii. Start the wave generator at the lowest wave period.
  iii. Collect data on the power generated by the boat for three minutes and record the average power over that time.
  iv. Increase the wave period slightly. The increments should be small enough that at least 20 data points are collected between the minimum and maximum wave period.
  v. Repeat step iii after each time the wave period is changed.
  vi. Plot the collected average power data to determine the best wave period for generating power. The inverse of this wave period is the natural frequency.
- Explanation of Data Collection Methods
  i. Collecting data experimentally is a simpler way to estimate the average frequency of the system, as opposed to computer simulations.
- Required Safety Precautions:
  i. The boat must be securely fastened to the sides of the wave tank to prevent collisions and potential damage to the boat or the tank.

TS-07: Charge Time

Validation Approach

Strategy:

- This procedure outlines the process for validation the Charging time Specification for the Autonomous Wave Powered Robot. This is an important specification to meet because the device needs to be able to regenerate power in a reasonable amount of time so that I can be used for mission activities. If the specification is not met, then the device would not be worthwhile to the consumer to use. The device would possibly more time charging than being useful to the consumer.
- For the charge time testing it would not be feasible to set the device in the ocean for many hours to test the functionality. Instead, the charge time can be calculated by a mathematical formula. The batteries need a certain amount of power for a certain amount of time to go from empty to full. This figure is in kilo watt hours. To find the charge time we would devide the capacity of the battery (kWh) by the power generated (kW) to get the number of hours needed to charge.

Resource requirements:

- Average Energy Generated
- Battery Capacity

The other resource requirements will be the same as the average power generated because that is where we will be getting data from.

- Functional Sub-Scale Device Constructed by Stevens
- Stevens Wave tank and all certified operating personnel
- Available timeslots at the wave tank
- Energy measuring circuit. Most likely a current shunt, but it is up to Stevens university's discretion
- Data logging device. Most likely a data logging voltmeter such as an oscilloscope

Detailed Test Procedures:

- Steps to follow:
  i. Preform Average Power Energy Generated test. See TS-04.
  ii. Using the specifications for the devices battery calculate the average charging time. $\frac{BatteryCap(kWh)}{AvePowerGen(kW)} = ChargeTime\ (hr)$
  iii. This specification can also be calculated for different ocean conditions
  iv. Determine if the specification meets requirements
- Explanation of Data Collection Methods
  i. We want to calculate the charge time rather than measuring it physically for two reasons. One we are not able to put the full scale model in the wave tank to time the charge time. Two we expect the charge time to be between 12-23 hours. This

would not be feasible to our team to test due to the duration. The calculated result should achieve a very similar performance to real life. Batteries have a charging curve that tapers as the battery becomes full. This means that at higher state of charges the battery will be able to accept less current. This would be a consideration for most other use cases of batteries, negating the formula presented above, but we are delivering so little current to the batteries that we will achieve a very liner charging curve thus the above formula should prove accurate.

ii. The ease of calculations and the difficulty of testing physically means that calculating charge time is the best option for the team.

- Required Safety Precautions:
  - i. Safety precautions will be the same as for the average energy generated (TS-04) because this procedure includes the same steps.
  - ii. Stevens University owns the wave tank, and they have their own set of safety precautions to use when operating the wave tank. I will touch on a few that may be relevant
  - iii. The large body of water poses a drowning hazard especially when the wave tank is enabled. Members in the vicinity should be comfortable with swimming
  - iv. The wave tank has large moving plates that could be a crushing hazard
  - v. The sub-scale model will have pinching points. This will need to be considered when handling.
  - vi. The Device will also be generating electricity near potentially conductive water. Electrical safety will need to be taken into consideration because of the increased shock hazard
  - vii. There most likely will be no batteries on this device but it is possible that there may be some. Lithium battery safety procedures will need to be followed if that is the case

TS-08: Roll Angle

Validation Approach

Strategy:

- Use a plumb bob and a protractor fixed to the mast of the boat the measure the angle from which it can still right itself.
- An external force will be applied to the boat from each side to determine the maximum roll angle the boat can withstand without capsizing.

Resource requirements:

- Plumb bob
- Protractor
- Wave tank
- A long stick or plank

Detailed Test Procedures:

- Steps to follow:
  - i. Secure the prototype in a calm wave tank such that it cannot move laterally.
  - ii. Apply a force slowly to one side of the prototype such that it begins to roll but does not move sideways.
  - iii. Record the angle at which the boat can no longer quickly return to vertical.
  - iv. Repeat the two previous steps for the other side, as well as the front and back.
  - v. Use the data from all four sides to determine an average roll angle and a maximum.
- Explanation of Data Collection Methods
  - i. Using an external force on each side of the boat will allow us to determine the maximum roll angle more accurately than simply placing it in an active wave tank.
  - ii. A plumb bob with a protractor is a very simple and cheap method for measuring vertical angles.
- Required Safety Precautions:
  - i. The boat must be securely fastened to the sides of the tank to prevent collisions and possible damage to the boat or the tank.
  - ii. Two ropes held by team members will be fixed to the top of the boat to prevent it from completely overturning once it reaches the tipping point.

TS-09: Max Customer Added Load

Validation Approach

Strategy:

- The customer has the option to add their own equipment or modules by mounting them to our boat. This of course adds weight to the boat. It needs to be ensured that the additional weight will not sink the boat. This means that the buoyant force must be able to accommodate for the additional load without sinking. This is an important characteristic to be validated as we need to be able to inform the customers on what max equipment weight they can install on the boat while keeping the product safe, afloat, and functional.

Resource requirements:

- Access to SOLIDWORKS 2021 is necessary.
- A full assembly of the product with materials defined in the assembly is required.
- Access to the kayak model suggested maximum load.

Detailed Test Procedures:

- Steps to follow:
  - i. Launch SOLIDWORKS 2021.
  - ii. Load the boat assembly.
  - iii. Suppress the two kayaks and the wave glider body and fins.
  - iv. Click on tools → evaluate → mass properties
  - v. Record the weight
  - vi. Multiply the suggested max weight for the kayaks from the manufacturer by 2 and consider this as the boat's buoyant force.
  - vii. Subtract the weight found in SOLIDWORKS from this max buoyant force.
  - viii. This will be the max allowable weight for customer added equipment.
- Explanation of Data Collection Methods
  - i. The manufacturer gives a max weight for each kayak. This weight includes a factor of safety. Thus, that factor of safety is still present in the value for the max allowable customer added load. The kayak weights do not contribute against their own buoyant force and the wave glider is designed to be neutrally buoyant, thus they are removed from the CAD assembly. Finding the weight of all components that are left gives a good idea of the weight experienced by the two kayaks. Thus, subtracting this weight from the doubled max kayak weight from the manufacturer (because there are two kayaks) give the max allowable customer load with a factor of safety.
- Required Safety Precautions:
  - i. Again, as this verification is completed entirely on a computer, the best safety precautions are to have comfortable wrist positions and to occasionally look away from the screen to reduce eye strain.

TS-10: Head on Impact with Rigid Object

Validation Approach

Strategy:

- The strategy that was used was impact testing of the prototype. The rigid object is made from a source that has similar components to ocean debris. The impact force will be measured with force gauge with multiple different angles and procedures. The testing strategy will be efficient to this target specification since the measurements are needed to see the impact.

Resource requirements:

- Rigid object
- Prototype
- motor
- Test data
- Force Gauge

Detailed Test Procedures:

- Steps to follow:
  - i. Make a prototype that can be easily separated
  - ii. Build a ocean debris that corresponds to the prototype weight
  - iii. Research and find the values of the impact and the timing first
  - iv. Test the impact on the ocean environment using the protype
  - v. Use force gauge to measure the impact on every angle, direction, and speed.
  - vi. Combine all the results of the prototype to use it on the product
- Explanation of Data Collection Methods
  - i. The data will be recorded by excel sheet with limited number of resources for a close calculation of the impact.
  - i. After the testing, the data will be organized in excel by angle, direction, speed, and time.
  - ii. Then the data will be calculated to find the maximum impact force that can be hit on the prototype.
  - iii. With the data, correlate to the product and measure the impact force.
- Required Safety Precautions:
  - i. The force gauge is needed for the experiment
  - ii. Testing should be conducted in an ocean environment
  - iii. Gloves are needed during the impact of the force gauge
  - iv. No ear or eye protection required.

TS-11: Buoyant Force

Validation Approach

Strategy:

- Every floating vessel must be buoyant. This is no different for the wave powered autonomous boat. For the boat to float at rest on the surface, the buoyant force must be equal to its weight. If the buoyant force is greater than its weight, it will rise. If the buoyant force is less than the weight, it will sink. The boat's weight should never be greater than th buoyant force. This is an important specification. If the weight is very close to the max buoyant force, a bit of water splashing into the boat could cause the weight to be greater than the buoyant force and sink the boat. By Archimedes' principle, it is known that the buoyant force is equivalent to the weight of the volume of fluid displaced by the object. Th max buoyant force would occur when the entire boat is submerged. Ideally, the weight of the boat would be less than that max buoyant force. Our goal, is to ensure that the max buoyant force is between 10,000 and 20,000 N.

Resource requirements:

- Ideally the boat could be tested in a large submersion tank and use a set up with load cells to measure the buoyant force. However, access to such a tank and fully submerging the

  boat is not reasonable for the fiscal and time restraints. Thus, determining the max buoyant force will be done by doing a volume analysis in SOLIDWORKS. This analysis requires access to SOLIDWORKS 2021, a fully detailed and completed assembly model of the boat, and a calculator for making computations.

Detailed Test Procedures:

- Steps to follow:
  - i. Launch SOLIDWORKS 2021.
  - ii. Load the complete and detailed assembly of the boat.
  - iii. Save a copy of the entire assembly as one solid body.
  - iv. Select Tools → Evaluate → Mass Properties...
  - v. Then, record the volume of the assembly.
  - vi. If given in units other than m3 , convert the volume to m3 and document.
  - vii. Use external resources, such as the internet, to find a value of sea water density in kg/m3 and document.
  - viii. Use and document gravitational acceleration as 9.81 m/s2 .
  - ix. Calculate and record the buoyant force by multiplying sea water density, gravitational acceleration, and assembly volume.
  - x. Compare result to specification.
- Explanation of Data Collection Methods
  - i. Using a tank to fully submerge the boat and some load cell system to document the buoyant force is unrealistic for the time and budget constraints. Using an analysis in SOLIDWORKS is perfectly acceptable and should give an accurate value. There is no need to repeat steps multiple times to collect several values, as the computer will give the same result each time.
- Required Safety Precautions:
  - i. As this test consists of an analysis of a model on a computer, there are not many safety matters to consider. However, proper usage of a computer such as comfortable wrist position and occasionally looking away from the screen can reduce joint and eye strain.

TS-12: Cost

Validation Approach

Strategy:

- The strategy that used was a comparison between the products. The team is assigned to each part that they are responsible for searching online. This will prevent any overlapping of research. The comparison is a great strategy for this target specification since the cost for every part is different and the spec differs piece by piece.

Resource requirements:

- Excel sheet
- Internet
- Comparing websites
- Calculator
- Survey(possibly)

Detailed Test Procedures:

- Steps to follow:
  - i. List all the materials and parts for the boat and the electronics that is necessary
  - ii. Organize the budget and separate by parts for spending
  - iii. Research and find the cost for the materials and exclude the cost if the material is owned
  - iv. Make a table that labels each cost of the materials with cost range
  - v. Combine all the cost for the parts and compare with the budget
- Explanation of Data Collection Methods
  - i. The data will be recorded by excel sheet with limited number of resources.
  - ii. The samples will be measured by dollar on the budget.
  - iii. At least 10 combinations of the material cost will be measured for better quality and cost.
  - iv. The datapoints will be not get averaged since there are limited number of budget that we can spend so the team will consider the cheapest cost.
  - v. The measurement will be done by the whole team, and each will get assigned to a part that they are charged with measuring.
  - vi. Microsoft excel will be crucial for this collection method since everything will be done by excel sheet.
- Required Safety Precautions:
  - i. The only safety procedure for this measurement will be the origin and location of the materials.
  - ii. Since there are not much time for us to do the project, the team cannot risk buying any foreign country product even with cheap cost.
  - iii. The testing will be performed inside and will be done online.

TS-13: Service Life

Validation Approach

Strategy:

- Everything has a service life. It is important to have an estimate of the expected life of a product so a customer has a good idea of when the product may need to be replaced.
- The service life of a product can be greatly improved if it is maintained properly.

Resource requirements:

- Estimated service life of components used in the manufacturing of the device. The component that is likely to have the smallest service life will likely determine the overall service life of the device. Therefore, datasheets for all major components used in construction will be required.

Detailed Test Procedures:

- Steps to follow:
  - i. Due to the sheer impossibility of testing for months at a time an estimate will need to be determined by generating an analytical equation.
  - ii. Find the lowest listed service life of a component from datasheets.
  - iii. Estimate how much the life of the system can be extended based on regular maintenance and replacement of parts.
  - iv. Generate an equation using the factor method outlined in Hodve's paper that could help predict the service life of the overall device.
- Explanation of Data Collection Methods
  - i. Data will be recorded in an excel sheet.
  - ii. A model will need to be generated based on the values obtained from datasheets.
  - iii. This model will output an estimated life for the device based on Hodve's factor method.
- Required Safety Precautions:
  - i. No real safety precautions are required as this is deskwork.
- Reference documents
  - i. https://www.irbnet.de/daten/iconda/06059020143.pdf

TS-14: Bounding Volume

Validation Approach

Strategy:

- Bounding volume is the volume of a rectangular prism which fully encloses an object. A sphere with diameter 1 m has a bounding volume of 1 m^3 since it is enclosed by a 1x1x1 cube.
- The bounding volume of each subassembly and the entire assembly will be measured.
- This is important for travel. The type of vehicle and whether we move it disassembled or assembled will be informed by the bounding volume.

Resource requirements:

- Measuring tape

Detailed Test Procedures:

- Steps to follow:
  - i. The two subassemblies (heave frame and boat) will have their length, width, and height measured at their greatest extent.
  - ii. The full assembly will have its length, width, and height measured at their greatest extent.
  - iii. The bounding volume will be calculated as V = L*W*H for each three iterations
- Explanation of Data Collection Methods
  - i. The maximum length, width, and height of each assembly when multiplied together form the bounding volume. This will be recorded for all three systems, heave frame, boat, and the entire assembly.
- Required Safety Precautions:
  - i. There is no real danger in this verification, we are only measuring parts with a measuring tape.

TS-15: Movement Efficiency

Validation Approach

Strategy:

This document describes the validation approach for the Wave Powered Autonomous Robot's movement efficiency. The Wave Powered Autonomous Robot Will be built by Team 43. This device will be able to navigate autonomously in the ocean and generate its own power from the waves beneath it. The device that will need power to spin propellers for movement capabilities. It is of great importance that the power consumed for motion is within the target specifications that the team outlined.
When the device is constructed to its final shape and mass then the movement efficiency can be tested. To do this the device will be placed in an open body of water and then driven under power. This will draw power from the onboard batteries. In our electronics system we plan on having a current measuring device called a current shunt as well as a voltmeter. These two measurements can be multiplied to report the power at any given time. This information can be fed back to the onboard computer at regular spaced intervals, most likely multiple times per second, and the computer can record this data. We will also have an on-board GPS that will inform the computer where it is located. With the GPS data it is possible to calculate the traveled distance. We will record the GPS coordinates to the computer's storage at regular intervals. Later this data can be extracted from the on-board computer and then the distance traveled can be calculated as well as the watt hours consumed. This data can then be used to calculated km/kW hr, the given specification unit. We will then compare it to our specification to see if it passes or fails.

Resource requirements:

- An open body of water that permits us to test our device
- A constructed wave powered autonomous robot which at the minimum is required to be in the form of the final design and have a functioning electronics system onboard capable of control, data logging, power measurement and delivery, as well as GPS enabled data.
- Charged batteries contained within the device
- A remote control for steering the device while testing
- A computer to download the data from the on-board computer
- Possibly a vessel to drive alongside the device when it is being tested

Detailed Test Procedures:

- Steps to follow:
  - i. Arrive at permitting body of water with all resources ready
  - ii. Construct and configure the device to be water ready
  - iii. Preform a controls and communication test on land before deploying
  - iv. Test that data is being logged properly, can be viewed over telemetry
  - v. Deploy device into body of water
  - vi. Test functionality of device when it is near the shore
  - vii. When confirmed then proceed to drive the device thought the body of water
  - viii. Continue this test for as long as possible to collect the most data
  - ix. Steer device back to shore to be extracted
  - x. Remove device from body of water
  - xi. Turn off device and trip the main breaker
  - xii. Extract data from data logging
  - xiii. Process data and calculate the km / kW hr
  - xiv. Check to see if target speciation is met
- Explanation of Data Collection Methods
  - i. The data collection method should prove to be the most accurate way to determine if the device met the required specifications. Instead of doing a simulation or finding the average speed and average power consumed for an instant in time the test would be performed over many minutes if not hours. This allows for us to have a higher confidence level than if we extrapolated from instantaneous measurements. The actual data collection from the GPS and the Power meter should be accurate as both are calibrated pieces of equipment. The GPS does have some inaccuracies but over hours of data the impact of the drift should be very minimal on the actual speciation's. The same can be said for the power meter.
- Required Safety Precautions:
  - i. When dealing with any time our device will be charged and or powered on awareness will need to be had by all personnel present. Our device functions off electricity and we are putting it in a possibly conductive liquid so extra care must be taken to not allow any shore circuits or electrocutions. The voltage is low enough to not be concerning to the health of personnel, but it will be avoided regardless. Our device also has propellors that spin and can slice flesh. They will be protected and there will be no personal near the device when it is operating. We also have many

moving parts so we will have pinch points these will be labeled by the team. Since we are in an open body of water for testing the personnel involved should have experience swimming and if out on the water live preservers should be worn.

TS-16: Maximum Harvestable Wave Amplitude

Validation Approach

Strategy:

- The team will benefit from knowing the maximum harvestable wave amplitude. With this data, the team will be able to make recommendations about where the boat would be best deployed. If the boat were to be deployed in an area with a wave amplitude greater than the maximum harvestable wave amplitude, the boat will not be able to capture energy at the peak and trough of the wave. In the interest of maximizing energy capture, the boat should be operated in conditions where the wave amplitude is below the maximum harvestable wave amplitude.
- The heave frame is the structure that supports the wave glider. The boat hull is able to travel the length of the heave frame. Thus, the length of the heave frame represents the maximum wave amplitude the boat is able to harvest.

Resource requirements:

- Measuring tape

Detailed Test Procedures:

- Steps to follow:
  - i. The length of the heave frame in contact with rollers will be measured.
- Explanation of Data Collection Methods
  - i. The length measurement of the heave frame will be recorded.
- Required Safety Precautions:
  - i. There is no foreseeable danger with this validation,

TS-17: Max Speed

Validation Approach

Strategy:

- Use the location difference of the boat between a specific time interval to calculate the speed of the boat under ideal wave conditions.
- The onboard GPS on the boat will provide accurate position and time data from which the speed can be determined.

Resource requirements:

- GPS Position and Time Data
- Wave Tank

Detailed Test Procedures:

- Steps to follow:
  - i. Secure prototype at one end of the wave tank so that it always points forward.
  - ii. Lock the heave plate at the bottom position.
  - iii. Start the wave generator.
  - iv. Ensure GPS data is being collected at the fastest rate possible.
  - v. Once the boat nears the end of the wave tank, turn the wave generator off.
  - vi. Export the GPS data to a program such as Excel or MATLAB to calculate max speed.
- Explanation of Data Collection Methods
  - i. Using a wave tank will allow the wave glider to provide the maximum forward thrust.
  - ii. The onboard GPS will provide much more accurate position and time data than a stopwatch and meterstick could provide.
  - iii. As a precautionary measure, a stopwatch will be used to measure the speed of the boat at regular intervals to validate the GPS data.
- Required Safety Precautions:
  - i. The boat must be secured to the sides of the wave tank in such a way that it cannot accidentally damage the tank or the wave generator.

TS-18: Weight

Validation Approach

Strategy:

- There are two separate weight requirements for the boat and the heave frame.
- The heave frame must be less than 150 lbs.
- The boat assembly must be less than 550 lbs.
- Material and part selection will be performed with the weight limits in mind. Materials with high strength to weight ratios are ideal, like aluminum. Parts will be selected to minimize weight as well, batteries weight high charge to weight ratios are ideal.

Resource requirements:

- Bathroom scale
- Rigid platform for stacking parts

Detailed Test Procedures:

- Steps to follow:
  - i. The parts for each assembly will be gathered on a platform which rests upon the scale.
  - ii. The parts will be weighed. Multiple rounds of weighing may be necessary if all the parts of an assembly cannot fit on the scale at once.
  - iii. The total weight of each assembly will be compared to its threshold.
- Explanation of Data Collection Methods
  - i. Each assembly will be weighed to ensure that the final weight matches the design.
- Required Safety Precautions:
  - ii. During weighing, heavy parts like the wave glider or frames should be carried by two people to reduce the chance of dropping and damaging parts/people.

TS-19: Deployment time

Validation Approach

Strategy:

- The strategy that used was a comparison between the products. The team sets a certain point for the deployment of the boat and measures the time for each component. Then the team will be redoing the deployment with a different strategy and see which one can shorten the time for the deployment. Comparison is a great strategy for this target specification since shortening the deployment time is crucial for validation.

Resource requirements:

- Excel sheet
- Stopwatch
- Truck
- The product (boat)

Detailed Test Procedures:

- Steps to follow:
  - i. Put the boat on the truck for the measurement
  - ii. Organize on the excel for the unboxing of the product including assembly, unpacking, carrying, and lowering on the lake.
  - iii. With the team ready for the testing, test the unboxing and the deployment of the product with a different strategy.
  - iv. The measurement will be done with a stopwatch.
  - v. Organize the strategy on excel sheet for comparison.
- Explanation of Data Collection Methods
  - i. The data will be recorded by excel sheet with different components.
  - ii. The samples will be measured by stopwatch.
  - iii. At least 5 combinations of the strategy are needed for precise comparison of the time.
  - iv. The measurement will be done by the whole team, and each will get assigned to a part that they are charged with measuring.
  - v. MS excel will be crucial for this collection method since everything will be done by excel sheet.
- Required Safety Precautions:
  - i. During the unboxing different tools are needed to unbox instead of using hands.
  - ii. The parts of the boat are heavy and pose a dropping hazard
  - iii. There are pinch points on the device
  - iv. The electrical system contains Lithium batteries which need to be treated with care
  - v. The testing will be done on the lake. Everyone should be comfortable with open water

TS-20: Operating Noise

Validation Approach

Strategy:

- The team will measure the operating noise of the device.
- The noise should ideally be under 50 dB however any value below 100 dB will be acceptable
- This is in place to reduce the effect the device will have on surrounding wildlife.

Resource requirements:

- Decibel meter
  - i. Can possibly be a phone with an app.

Detailed Test Procedures:

- Steps to follow:
  - i. The ambient noise of a body of water will be measured.
  - ii. The device will be placed in the water.
  - iii. The device will be set to operate under ideal normal conditions.
  - iv. The underwater operating noise of the device will be measured and subtracted fron the ambient noise.
  - v. This data will be plotted to see if the device ever exceeds the operating noise thresholds.
- Explanation of Data Collection Methods
  - i. The data will be recorded in an excel spreadsheet.
  - ii. The operating noise will be measured throughout the operation cycle. The noisiest part of the cycle can be identified.
- Required Safety Precautions:
  - i. Only a team member comfortable with swimming will be operating the decibel meter underwater.
  - ii. The decibel meter will be in a protective casing to prevent water related damage and a possible short circuit or other water related accidents.