

Bubbles Under the Sea



Department of Electrical Engineering and Computer Science

University of Central Florida

Dr. Lei Wei, Dr. Samuel Richie

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Group 19

Jacob Lavoy, Electrical Engineer

Madison Melton, Electrical Engineer

Avery Mills, Computer Engineer

Joshua Nichols, Computer Engineer

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1. Executive Summary

As a number of activities revolve around water, it's no surprise that humans live near bodies of water such as rivers and oceans. As of 2011, "50% of the world's population lives closer than [three kilometers] to a surface freshwater body, and only 10% of the population lives further than [ten kilometers] away" [54]. NASA estimates that over one-third of the population lives within 100 kilometers of an oceanic coast [55]. Among the activities that can be done on or in the water, jet-skiing, sailing, wakeboarding, fishing, and scuba diving are among the most prominent. This means that for most water-based activities, a lot of time is spent seeing what is above or on the water's surface. But what about observing what's under the surface, and without the expensive gear typically required?

Our motivation in creating a remotely operated submarine is to do just that. A submarine like this could be deployed for utilitarian purposes such as finding items lost under the water, inspecting the undersides of aquatic vehicles or seaside structures for damage, or for conducting research. However, a more common use would likely be for underwater exploration and fun. In most significant bodies of water like rivers, lakes, and oceans there is a lot of life that can be observed. Other things can be looked at under the ocean's surface as well, like coral reefs, aquatic caves, and shipwrecks nearby to shore.

To facilitate this, we will be creating a remote controllable submarine with a multi-axis rotatable high-definition camera. This will allow the user to adjust where they are looking independent of the submarine's movement and track any items of interest. The user will be able to perform this adjustment with a dedicated two-axis joystick and see the changes on the controller's wide screen. The controller will also allow the camera to pan left to right as well as up and down via another two-axis joystick. The ability to pan and tilt the camera on a submarine that costs \$1000 or less is unheard of, typically found on submarines used for industrial applications or for research institutes and costing significantly more money.

The submarine will also come with an adjustable LED light. Adjustable LED lights are notable in that very few existing remote control submarines have the capability of changing their brightness. This tends to lead to harsh lighting in undersea pictures and video, where photographers only have the options of no light or a very bright light, with no options in the middle. For them, adjustments are made by changing the submarines position, which would be impossible if the submarine was in an enclosed area, or risk scaring the wildlife nearby. The ability to change the brightness is also important in places that have light-sensitive organisms, so an operator will be able to change the light on the fly.

So for research or for fun, our remotely operated submarine allows users to explore the underwater world with the vision capabilities of being there themselves. For people of all ages and abilities, with a longer battery life, this submarine will provide hours of good use and enjoyment.

2. Project Summary

There is no doubt of the need for such a project. Allowing an operator to have such an impressive remotely operated submarine such as ours and removing their need to be in the water themselves is only icing on the cake. The following section details the motivation, goals, and challenges in creating our remotely operated submarine.

2.1. Motivation

Florida's various beaches and rivers are very scenic and a big reason for tourists who come to the state. With some of our members regularly participating in community outreach programs for those with mental or physical disabilities, we had the idea of somehow helping these people to experience the same wonder and natural beauty of the ocean that they might otherwise not ever be able to fully explore. With this goal in mind, we drafted an idea for some sort of underwater camera that would allow them to maneuver and see what is under the water. With that, Bubbles Under the Sea was born with a clear goal to give people who are handicapped or otherwise unable to swim the ability to explore sea and river ecosystems.

2.2. Potential Customers, Sponsors, Contributors

We are our own sponsors. Our most focused audience is people who are handicapped or are unable to swim who want to see underwater for research and/or fun. We wanted to make the project on the cheaper side so that it would not be something that only some people can afford, expanding our customer base, especially with our goal in mind to give as many people as possible the ability to explore underwater.

2.3. Project Goals and Objectives

Our primary goal is to create a retrievable, remotely operated submarine that live streams its video feed back to the user. Most underwater submarines on the market cost above \$1500, and ones below that price may have battery capacity for only two hours. As such, additional goals are to reduce the price below \$1000, for the submarine to be easily brought back to shore by the operator, and for the battery life to last as long if not longer than commercial products. Further goals are to provide multi-brightness LED lights, retractable cables, and to make the camera rotatable as part of supporting possible VR applications. The majority of remotely operated submarines on the market have lights that turn on and off, so having different levels of light would allow for adjustment in tight areas. Having too bright of a light may interfere with the operation of the camera, which would hamper the vision of the user.

Sub-goals have been identified for the controller itself:

- Ability to display live streamed camera footage.
- No more difficult to use than a standard game controller.
- Clarity of display in terms of reception and sun-glare.
- Keep less than one kilogram.

2.4. Stretch Goals

Some stretch goals were identified, to be completed if time allowed. Such goals include changing from a static, interchangeable camera, to a built-in camera capable of rotating 360 degrees horizontally, and 90 degrees vertically to allow for optimal aquatic life viewing. Adding VR viewing would increase the utility of having a rotating camera. Sonar range-finding could be included to allow for the rear of the submarine to detect when it is about to strike terrain, wildlife, or other objects. Two ideas exist that decouple the controller and the sub, such as an eject-able umbilical cable, or having the wire instead go to a buoy on the surface that transmits the video back via Wi-Fi. Other stretch goals include item retrieval abilities and possible graphics processing such as identifying and highlighting objects seen in the video.

2.5. Primary Design Challenges

There will be challenges in creating this submarine such as: maintaining high video quality over the transmission line, ensuring that power is distributed evenly among components, and not creating any short circuits. Additionally, the entire system must remain waterproofed to ensure the integrity of electrical components inside of the submarine.

2.6. Features for Final Demonstration

In our final demonstration, we intend to show that our submarine can be moved forward, backward, right, left, up, and down. We will also be able to show the video footage from the camera to see underwater. We will be able to demonstrate variable headlights, as well as the range and depth capabilities of the sub.

2.7. Market Analysis

Analysis of competitive products and projects has shown that while existing products are certainly portable, larger models are bulkier requiring the use of both hands to deploy, and other models have significant differences in battery life for the different speeds of the vehicle. These same products focus on being easy to use and having accurate sensors, which is something we intend to continue with our solution.

Additional research has shown that the majority of submarines sold for leisure are sold above \$1000, often offering a controller with a screen, connecting cable, and single-camera vision system. Having cameras on board that are 1080p quality is regular, with the more expensive submarines coming with 4K quality. These subs also come with lights that are at least 250 lumens which are provided for low visibility situations. Running times of one-two hours are also common, and along with the other feature mentioned establishes some baselines for our engineering requirement specifications. The following paragraphs cover some existing products on the market with their specifics.

On the lower end of the scale in terms of size and cost is the PowerVision PowerRay Wizard sold at \$999 dollars. Weighing in at 3.8 kg, it operates within 0-40 degrees Celsius waters, and is capable of livestreaming 4K footage at 25 fps. It is also able to last in the water for four hours when in light use, but only half an hour in high-speed racing mode. It moves around with its three thrusters to achieve its maximum cruising speed of 1.5 m/s. On the higher end of the scale is the \$1899 QYSea Fifish V6 underwater submarine. It matches the speed of the PowerRay and is capable of streaming 4K footage at 30 fps as deep as 100m below the surface. With a 162-degree ultra-wide lens, and two 2000 lumen lights, the submarine is capable of watching anything in the environment it's deployed in. The submarine has 6 degrees of freedom, and as such can thrust horizontally and vertically with its six-thruster configuration. However, with a weight of 3.91 kg, it is certainly one of the heavier subs available.

2.8. Previously Discussed Design Ideas

One idea that we discussed was the idea of using a propulsion system similar to a whale's tail to steer and propel the sub. After our research, we decided that the umbilical cable would get tangled with the tail too easily and would cause a serious damage after long term use. Instead, we decided to go with the idea of one large rotary blade on the back and one smaller rotary blade on the bottom of the sub. This way, the large blade would be able to propel the submarine forward, and the little one can guide and direct the sub. Another idea discussed was the use of a single computer on-shore, with signals sent to the submarine and controller separately and broken out into the necessary signals. However, it was determined that a two-computer system would be used, one on board the submarine and another in the controller in order to speed up video encoding/decoding, speed up video transmission, and to simplify the decoding of command signals from the controller. In particular, we wanted to focus research on on-board computers with gigabit Ethernet ports, in order to maximize the speed of video transmission.

2.9. Engineering Requirement Specifications

The main requirements that we were looking to accomplish with our project were the diving depth, the video quality, and variable headlights. The reason these

three were selected was because most submarine submarines that go into the water don't often display video and when they do it isn't that high of quality unless it's a severely expensive submarine. We wanted to achieve a cheaper alternative while maintaining the quality. With the diving depth we wanted to achieve at least 5 meters so that the submarine could be used in most lakes, ponds, and springs. Even though the dive depth is not that large achieving a higher goal is still present and will be challenged constantly throughout the creation process. Each of them are shown below in Table 1.

Table 1: Major Requirements

Major Requirements	
Requirements	Specifications
Diving depth	At least 5 m
Cable can carry a video feed	At least 1080p
Variable Headlights	Settings between 150 lumen and 1000 lumen.
Can resist cold and warm temperatures	4 - 33° C
Umbilical cable length	15 m
Power requirements	<250 W
Production costs	Should not exceed \$1000
Battery life	>3 hours when fully charged
Camera can be rotated	60 degrees left to right
Weight	No more than 8 kg
Total Volume	No larger than 0.03 m ³

The wide variety of existing submarines led us to define each of the major requirements with range qualifiers for our own product to achieve. The numbers chosen serves as an average of the abilities of all of these products.

2.10. Project Decision Matrix

Table 2 below contains the four highest ranking ideas proposed by members of our group for our Senior Design project. We ranked our ideas by way of cost, sponsorship, familiarity with technology, chance for learning, and motivation and chose our final project idea based off the final score. Before proceeding with the submarine, we looked at several other projects proposed by the group, including automated windows, a vacuum tube amplifier, and computer security peripheral, with the former two ideas being the most developed in terms of goals and requirements.

Table 2: Project Ideas

Project Decision Matrix						
Idea	Cost	Sponsorship	Familiarity with Technology	Chance for learning	Motivation	Total score
Underwater Submarine	2	-1	3	4	4	12
Automated -Windows	1	-1	4	3	3	10
Vacuum Tube Amplifier	4	-1	1	2	2	8
Security Peripherals	3	-1	2	1	1	6

The automated window system would be a system designed to fit onto existing windows and would open based on the indoor and outdoor temperatures as well as the crime level of the surrounding area. It would tie into home automation systems and be controlled by apps for ease of use with windows being individually tunable. However, major design challenges that needed to be overcome included ways to keep it safe to use around kids and resolving how users interacted with the system in high crime areas.

The Vacuum Tube Amplifier came as a suggestion from family of a group member, with the goal of enhancing the power and capabilities of the analog electrical components, as well as the digital interface. It would be based on the design and work of the 2013 Senior Design project and would be assisted with existing documentation and schematic work. However, it comes with the challenge of playing with high voltage components, as well as the need to study an unfamiliar design and augment rather than replace sections of the overall design.

Figure 1 below assigns components of the project to team members based on which team members will be most efficient and to allow room for design work. Due to some shared electrical and programming experience amongst team members, components may be labeled with multiple team members.

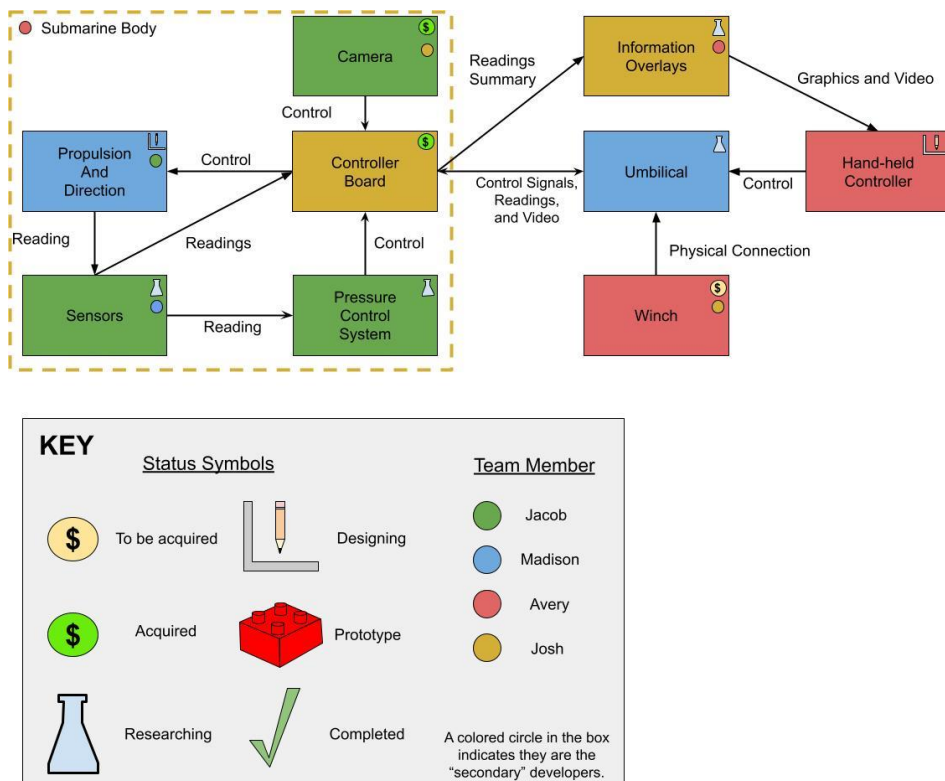


Figure 1: Role Assignments Block Diagram (Created by the Authors)

There are some important distinctions between the design and selection of individual components and the tasks listed in the above diagram. Because of the physical proximity and similar electrical requirements, propulsion and direction were grouped together as one task. The camera, on-board computer (labeled here as a controller board due to the possibility of not having chosen a microcomputer), and information overlays are handled by a single team member due to their physical proximity and great degree of programmatic interaction. Additionally, for readability, the hand-held controller has been combined into a single task but is a wiring and programming effort itself.

2.11. House of Quality

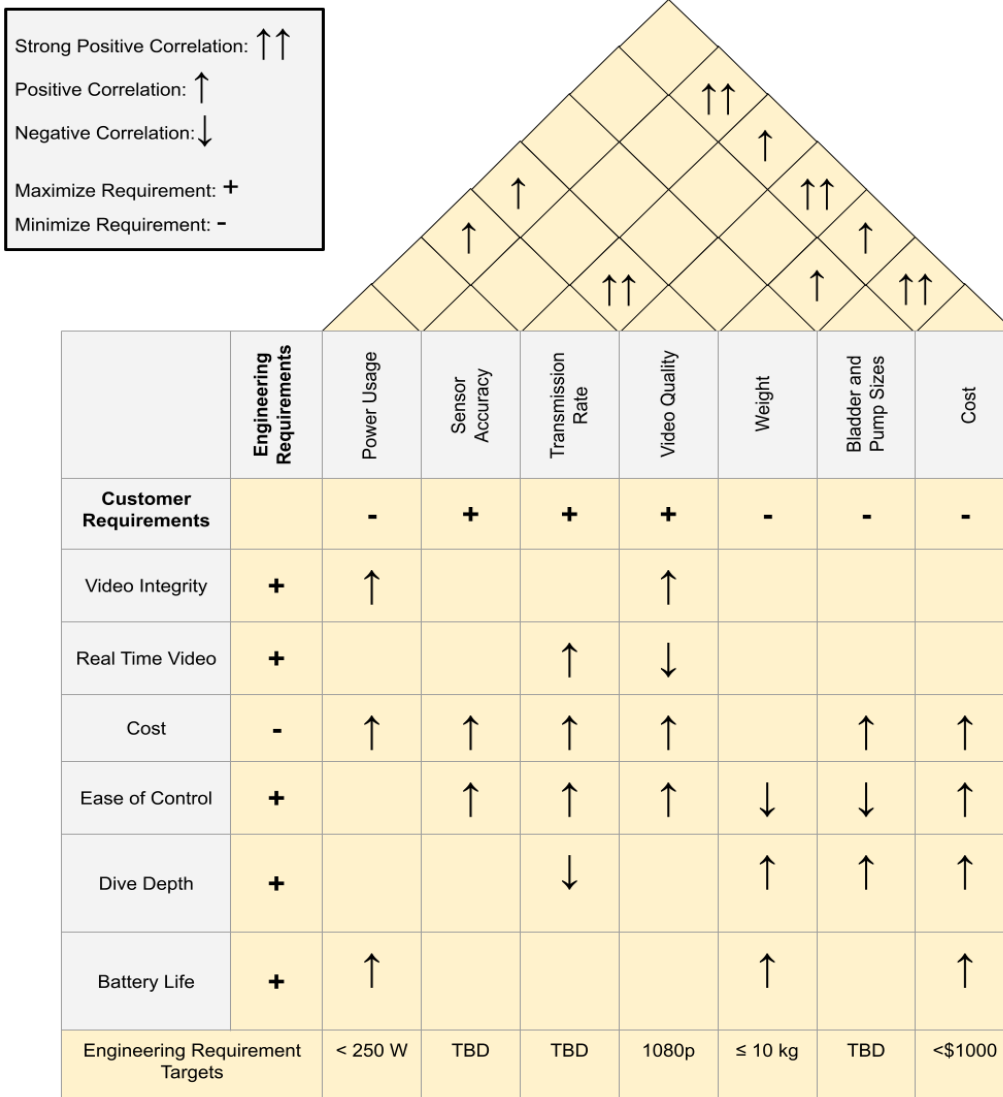


Figure 2: House of Quality (Created by the Authors)

The House of Quality shown in Figure 2 incorporates the customer and engineering requirements that we identified to be most important to a remote-controlled submarine. Trade-offs were discussed such as the one between weight and ease of control, which will have significant influence on the physical design. Different interpretations exist for how a House of Quality should be read, so we defined a positive correlation to mean that as one quantity increases, the other will also increase. These relationships are also being defined from the day-by-day viewpoint, rather than over the operational lifetime or in speculative scenarios, which can change the definition of a relationship. For example, during regular use the sensor accuracy should not be affected by the battery life but in

the case of a low battery, the design may necessitate shutting down sensors to preserve a video feed.

The House of Quality shown above reinforces notions that we had regarding the engineering requirements of the design. For example, it is reasonable to expect that a higher transmission rate would result in an easier time controlling the submarine.

2.12. Design Ideas

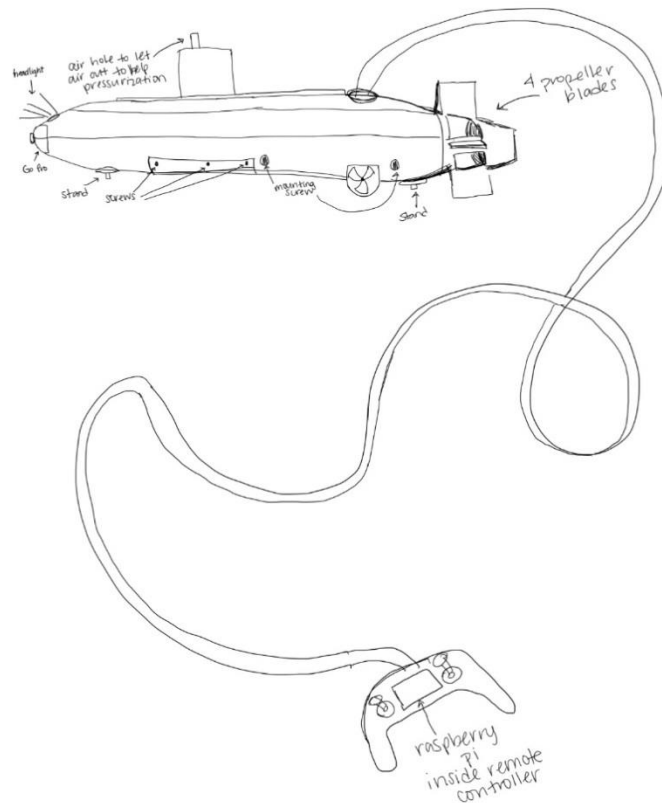


Figure 3: Design Idea (Created by the Authors)

Figure 3 shows our basic idea of how we should connect the controller to the winch and the winch to the submarine. We would have sealant on the outside of the camera's case to attach to the housing. There will be a hole in the housing at some placement with a grommet that would allow for the cabling to attach to the camera and the propulsion system. The camera would stream live video data to the computer through the cable. We will have metal shielding around the cable to make sure that it would not deteriorate when rubbed against rocks/coral or if bitten by a fish with teeth. The spool of wire would have an emergency crank in case it runs out of power and we need to retrieve the submarine from the water. The camera would be at the front of the submarine to get the best footage of the

ecosystems seen. The micro-USB cable would be attached to the camera at one end and the Raspberry Pi at the other end.

The controller would contain a Raspberry Pi with a screen where we will see video footage as well as readings from the pressure sensors inside the hull and the status of the motors.

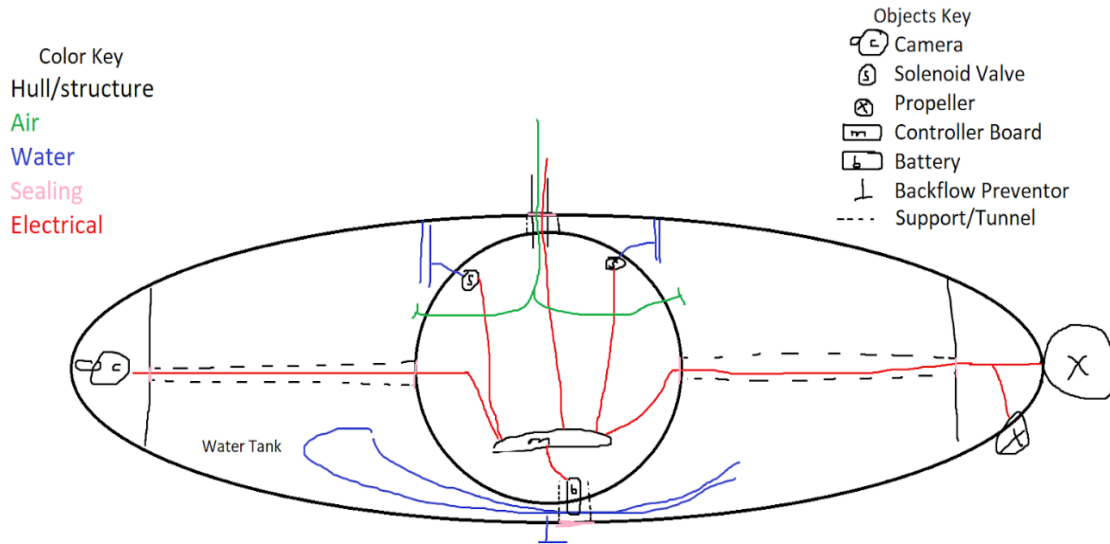


Figure 4: Structural Plans for the Submersible (Created by the Authors)

Figure 4 was made to show what pieces will be essential to giving the submarine the ability to navigate water. We have decided to go with a pressurized double hull so that we can control its buoyancy and depth in the water using the space between outer and inner hulls as a fillable water tank. We would also have three airtight interior hulls for storing the electronic pieces needed, located at the front, center, and back. The center hull would be holding the controller and most electronics, being supported by struts that act as tunnels to carry wiring to the other two air chambers. Around the center interior hull would be an external hull that would allow the submarine to fill up with water so that it would be able to dive easier. This tank would be filled with water by two solenoid valves on either end of the center hull, and filled with air by a pump that would come in through the umbilical cord with multiple back-flow preventers to allow proper drainage.

With underwater navigation comes a variety of challenges when dealing with movement. Due to the submarine being in a constant fight between sinking and floating back up to the surface, the design in Figure 5 incorporates a control for the rear rudders allowing us to redirect the submarine in a new direction to adjust. The controller will also have bladder controls, allowing either air or water to be added to the sub. The rear rudders and forward movement can be locked

to allow changing of the pitch, either descending further or to escape the current water depth.

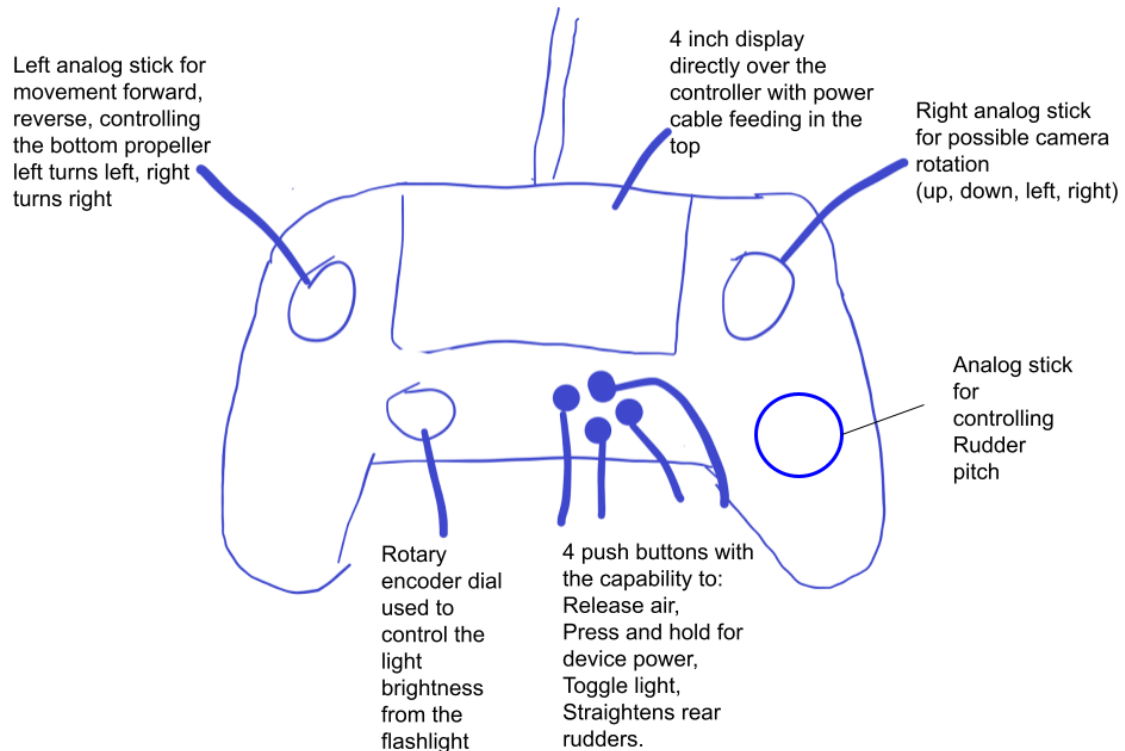


Figure 5: Initial Controller Design (Created by the Authors)

There will be three analog sticks allowing control over the sub. One stick adjusts the camera's view so that should we need to pan the camera to catch something moving across the submarine we easily can. The second analog stick would be for movement, so the submarine can move forward and backward using the main rear propeller. It will also have the capability to steer left and right using a smaller propeller that rests on the bottom of the sub. The third analog stick controls the rudder pitch. The rotary dial on the bottom right of the controller is what allows the headlight to be a variable intensity should it ever need to be dimmed or raised. The four push buttons on the controller will control the air/water release, toggling device power, toggling the headlights on and off, and to reset the rudders to a position that allows the submarine to move in a straight line. The main area of the controller contains a four-inch display screen that rests on a Raspberry Pi that is embedded into the controller. This display will allow us to directly see what the submarine sees and show warning messages from the sonar rangefinders on the sub. The Pi would be used to receive the digital signals from the submarine and send signals to the submarine for controls.

Figure 6 and Figure 7 below show a general idea of how the computer on board the submarine and the one in the controller will interact. The layout diagram also shows the ports expected to be used, as well as the key components and connections that will be used in the design. Note that for readability purposes the umbilical has been replaced with a dashed box with outgoing connections for both the submarine and the controller. Additionally, for diagram cleanliness, sensors are assumed to be connected to GPIO and are not drawn.

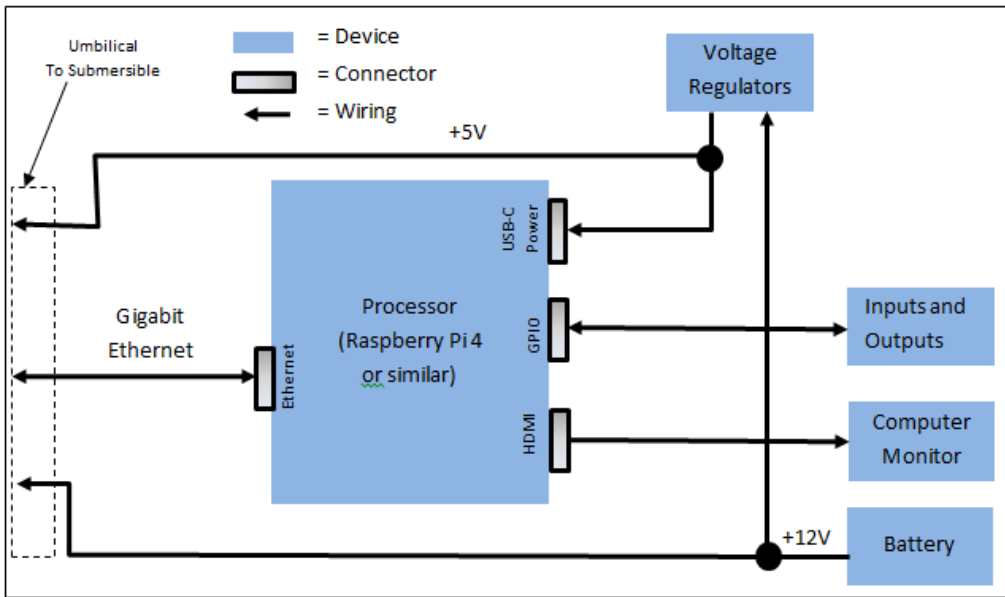


Figure 6: Controller Block Diagram (Created by the Authors)

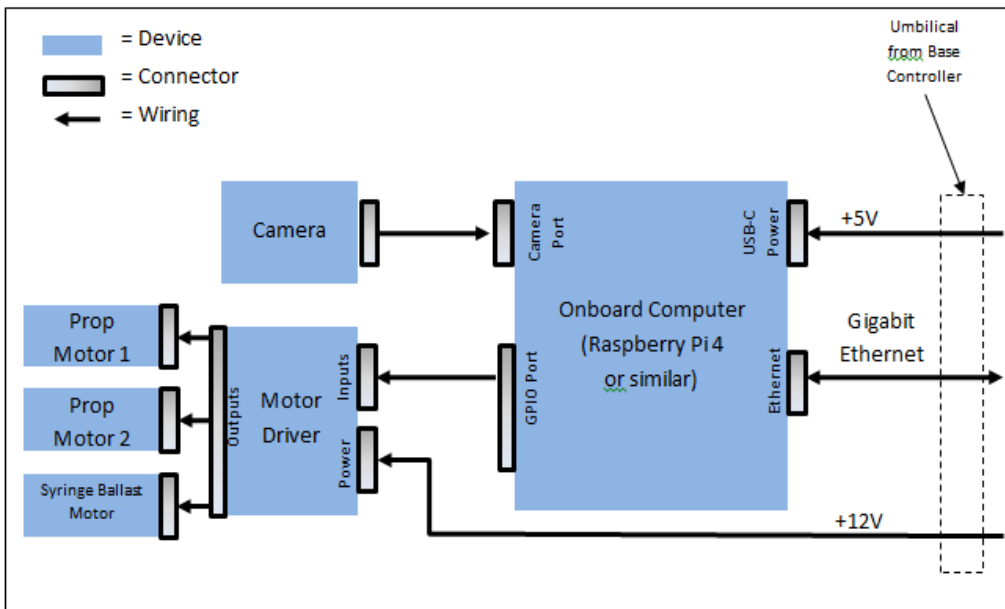


Figure 7: Submersible Block Diagram (Created by the Authors)

2.13. After Demo Goal Update

Two of the major goals listed in section 2.3 were realized to their fullest extent, those being the variable brightness LEDs as well as the rotatable camera. However, the time pressure to complete the project and have it in working condition meant that keeping the cost below \$1000 and having retractable cables were not possible. Furthermore, the sub-goals for the controller could not be tested under the conditions used for the demonstration video, nor were any of the stretch goals met. Additionally, the engineering requirements were adjusted to reflect the inevitable changes of direction that come with any project. They have been adjusted as per Table 3 below.

Component(s)	Parameter	Specification
Pan/Tilt Mechanism	Controllable Angle	Can use the controller to pan and tilt the camera in a 75° half cone.
Controller and Controllables	Action Delay	< 150 ms
Camera, Pis, Display	Image Delay	< 100 ms
Battery	Discharge Time	1 hour
Display	Framerate	30 frames per second
Propeller Motors	Speed	0.15 m/s
Headlight	Adjustable Brightness	0 - 8000 millicandela
Hull	Temperature Resistance	4 - 33° C*

Table 3: Adjusted Goals - Post Demo

All specifications outlined above were well beaten, most notably the pan/tilt rotation and display framerate. The pan/tilt was able to achieve 90 degrees left and right for panning, while also achieving 90 degrees up and down. These angles can be combined in any fashion and moved to by the controller. Likewise, the framerate can achieve and sustain 100 frames per second for long periods of time, and even during less favorable periods can sustain 50 frames per second or higher. The LEDs can also reach any brightness that can be reached in increments of 25. This 25 is arbitrary, and could be changed to more or less if any new design required it.

3. Part Research

This section contains any significant findings regarding each of the parts chosen for the submarine. Parts were chosen for their obvious price to utility measures and following each chosen part will be a selection of alternatives that were not chosen and why.

3.1. On-Board Computer

The brain of the submarine handles command interpretation, command execution, video processing, as well as the forwarding of video to the hand-held controller. It receives a number of inputs including instructions from the controller, direct video feed, along with depth and engine sensor data. It outputs compressed video, electrical signals to the motors and lights, and collected sensor readings to be interpreted by the hand-held controller. Communication occurs in a full duplex fashion. A summary of our findings can be seen in Table 4 below.

3.1.1. Raspberry Pi 4 Model B

The Raspberry Pi is a low-cost single board computer used mainly for the exploration of computation and programming ideas. The model 4B has several draws, costing only \$55 for its built-in Gigabit Ethernet, micro-HDMI, and USB sockets; 40 GPIO lines; community supported operating system; 4 gigabytes of RAM; 500 MHz GPU; and 1.5 Gigahertz 64-bit quad-core processor. The built in Ethernet capability and operating system would speed up development of video processing and forwarding substantially, the micro-HDMI connections would allow for direct interaction with any micro-HDMI camera chosen, and the amount of GPIO would allow for simplified wiring and component expansion opportunities. However, the lack of a significant analog to digital converter and singular MIPI camera interface would blunt the easy expansion of submarine capabilities as extra components would necessitate the use of some of the 40 available GPIO lines. There seems to exist contention in the online community about the direct streaming capabilities of the Raspberry Pi, with some members claiming that achieving full 1080p streaming is well achievable, while others claim that the resultant video is only in the 10-20 frame per second range, thus not meeting an engineering requirement if true.

3.1.2. Rock64 Media Board

While similar in form to the Raspberry Pi 4, the Rock64 Media Board has several design aspects that may make it an appealing choice when considered next to the Raspberry Pi 4 Model B. The lower cost of \$45 for the same size memory, along with its own 1.5 Gigahertz 64-bit quad-core processor makes it interesting. Along with that, it comes with a full-sized HDMI 2.0 port, Gigabit Ethernet, and a Debian Linux operating system. The main eye-catcher for this device is its supposed ability to support 4K resolution at 60 fps. The lack of built-in wireless

functionality and CSI camera interfaces would possibly make development more challenging.

3.1.3. NVidia Jetson Nano

A single board computer used by previous Senior Design projects, its impressive array of cutting-edge CUDA cores and dedicated graphics processing unit would make this the fastest of all considered systems. The board comes with a specially tailored Linux distribution provided by NVIDIA that has less community support, and the board is both larger and more expensive at a \$100 price tag. Normally used in service of large neural network and computer vision projects, the sheer power provided would not be fully utilized unless used for any of the stretch goals mentioned elsewhere in the document. It does have two MIPI camera ports, and its greater power would be useful in speeding up the encoding and transmission processes.

3.1.4. ameriDroid Odroid-C4

With four gigabytes of DDR4 RAM, gigabit Ethernet, HDMI 2.0 and USB 3.0 ports, a microSD socket, and 40 lines of GPIO, this would provide a fair alternative at a slightly higher price of \$50-\$65. In terms of size, the board measures 85*56*10 millimeters, making it very similar to the size of the Raspberry Pi 4B. The lack of built in Wi-Fi, Bluetooth, and micro-HDMI ports would be an inconvenience, though this may be offset by its ability to output 4K video at 60Hz through its HDMI display port.

3.1.5. Asus Tinker Board S

Coming with a 1.8 GHz 32-bit quad-core CPU, the ASUS Tinker Board S also comes with a 650 MHz GPU unit, two gigabytes of LPDDR3 Memory, sixteen gigabytes of built-in eMMC memory, and MIPI DSI/CSI support. Like the other single board computers, it has a growing community and uses a Linux distro. However, the board also has some notable drawbacks, in the form of USB 2.0 only ports, one full-sized HDMI port, the HD / UHD playback being entangled with the included media player, and costing an additional \$34 more than the Raspberry Pi 4 B.

3.1.6. On Board Computer Selection

Given the many choices on the market, the five shown here were the ones that were of most interest. Due to the features shown in Table 4, the Raspberry Pi Model 4B was the most cost-effective option. As the controller will also need communication and video display capabilities, it makes sense to pick the board with the smallest physical and price profiles. Additionally, the Raspberry Pi computers support a number of add-on modules that enhance its capabilities, such as sensors, displays, and camera modules. This made it worth investigating them as solutions to our other requirements detailed in later sections of this document. Below Table 4 are relevant notes that couldn't fit in the table.

Table 4: On-Board Computer Comparison

MODEL	Raspberry Pi 4 Model B	Rock64 Media Board	NVidia Jetson Nano	ameriDroid Odroid-C4	Asus Tinker Board S
Cost	55 for 4 GB (Sparkfun)	45 (reseller)	100	56	93 (reseller)
Size	85 x 56 Mm Note 3 Note 5	9 x 5.5 inch	70 x 45 mm Note 5	85 x 56 x 10 mm Heatsink adds 10 mm height	3.4 x 2.1 Note 5
Ethernet	1 GB	1 GB 1 WiFi 802.11 /b/g/n	1 GB	1 GB	1 GB 1 WiFi 802.11 /b/g/n
Video I/O	2 micro HDMI Ports (4K) Note 1	HDMI 2.0a output up to 4K@60Hz NO INPUT	1 MIPI-DSI, 1 HDMI 2.0a/b Note 2	HDMI 2.0 Supports add-on touch screen display NO INPUT	1 MIPI-1 HDMI Note 4
Storage Ports	2 – USB 2 2 – USB 3	2 – USB 2 1 – USB 3 1 – eMMC 1 – µSD	3 – USB 2 2 1 – USB 3 1 – eMMC	1 – USB 2 4 – USB 3 1 – eMMC 1 – µSD 1 debug UART	4 – USB 2 1 – eMMC 1 – µSD
RAM (GB)	2/4/8	4	4	4	2
Processor	Broadcom BCM2711 Quad-core Cortex-A72 (ARM v8) 64-bit SoC @ 1.5 GHz	Rockchip RK3328 Quad-Core ARM Cortex A53 64-Bit 1.5 GHz	ARM® Cortex® - A57 MPCore (Quad-Core) 1.43GHz	Amlogic S905X3 12nm Processor Quad-Core Cortex-A55 (2.016GHz) ARMv8-A	Rockchip Quad-Core RK3288 processor Quad-core Cortex-A17 (ARM Mali)
GP I/O	54	31	15	NO MENTION	40
Temp (°C)	0 to 50	No spec	-25 to 97	No spec	0 to 60
Power	5V @ 3A (15W)	5V @ 3A (15W)	5V (10W)	12V @ 2A (24W) recommended Accepts 5.5 to 17V	5V @ 3A (15W)
OS	Raspberry PI OS included, Supports Linux	Linux	Linux	Not Specified	Tinker OS included, Supports Android, Linux

Note 1: 2 Camera Serial Module Inputs available separately, discussed in the camera section.

Note 2: Dedicated RAW to YUV processing engines process up to 1400Mpix/s (up to 24MP sensor) MIPI CSI 2.0 up to 1.5GBps (per lane) Support for x4 and x2 configurations (up to four active streams). Includes multiple video decoders and encoders.

Note 3: Connectors protrude up to 5 mm.

Note 4: Includes ARM® Mali™-T764 GPU.

Note 5: Height not specified.

3.2. Battery

From the power analysis that we performed - shown in detail in Section 3.13 - we know that we will need a significant amount of voltage and current to completely power all of the components in the submarine. The main battery will need to supply enough power for both Raspberry Pis, the headlamp, and the sonar sensor. The propellers take up a significant amount of power and current. Because of this, we decided that we would need more power than just what can be transferred through Power over Ethernet. We have to add additional batteries for the propellers.

We cannot use voltage regulators on the PCB to control the navigation, since the motors need as much current as possible, so we have decided to use speed controllers to regulate the power going to each of the motors. Each motor will have its own battery and speed controller, making for four batteries, four 4-speed controllers, and four motors.

3.2.1. Main Battery – VISET Ebike Battery Pack

The VISET Ebike Battery Pack 36V 10 Ah battery [15, top image] (Figure 8) was proposed as the main battery, because it will produce enough current to sufficiently power all of our components with their respective nominal voltages and currents. This battery is also waterproof in case it gets wet while in the submarine such as if it rains while the submarine is in use or if it needs to be attached to the submarine if we have issues with it floating too much. The battery has a light indicator that shows the battery power level on the side, as seen on the left in Figure 8 below. This gives us an advanced warning for when we need to bring the submarine back to the submarine or shore.

We know this battery is a little on the heavy side weighing in at 2000 grams, but we figure that because it is waterproof and supplies enough power, then the weight can be overlooked. However, the calculations of voltage and current did not consider what the Power over Ethernet PSE component needed. After looking at the requirements for that component, we realized that this battery

would not work, since that component needs between 51-57 volts. The battery costs \$170 and has a size of 195*90*70 millimeters. As an additional bonus, the battery comes with built-in battery management system protection, for protection against overload, excessive discharge, or short circuits.



Figure 8: Viset Ebike Battery

3.2.2. Main Battery – Three Makita Lithium-Ion Rechargeable Batteries

After working on building the schematic for the PCB, we found that instead of a 48 V battery, we need something in the range of 51-57 V per the datasheet for the LTC4291-1 4-Port 802.3bt Power over Ethernet PSE Controller. As such, batteries with greater supply voltages were investigated. If we put three of these batteries together in series, we get 54 volts at 5 amps, which would satisfy our design criterion. This kind of battery however has a larger profile due to being in a larger case of 76.5*171.5*248 millimeters but weighs significantly less at 635 grams per battery. However, each battery is more expensive, with an average price of \$140, so buying three of these would take a significant part of the budget.

The cost for the prototype would be alleviated somewhat due to a team member already owning one of them. As seen in Figure 9 below, this type of battery has a battery level charge meter, so that we can see when it is about to run out of charge to make sure the submarine is above water before the battery dies. Also, it has a clip feature so that the battery will clip in tightly when it is being used.

Usually, this type of battery attaches to drills, vacuums, saws, blowers, and other things. Inside the housing are several little batteries chained together. However, if we put three of these batteries together in series, we would get the benefits of this battery times three.



Figure 9: Makita Lithium-Ion Battery

To chain these three batteries together, we have decided that we could use a 4-battery holder seen in Figure 10 below. This holder would keep the batteries in a special place together. Where the batteries hook in electrically, we would make a soldered connection and run wires on the backside to connect them all in series to give us the 54 V.



Figure 10: Makita Four-Battery Holder

3.2.3. Main Battery – 60 V Greenworks Battery

The battery shown in Figure 11 supplies the perfect amount of voltage and current that our project needs. This battery supplies 60 V at 2.5 Ah. Also, it is a great size and weight, so that it is manageable to work around and transport. It is

lightweight, as it is intended for use on items such as a weed-eater or other power tool of the same size. There are LED lights shown in the bottom of this figure that show the battery life left, so that we don't have to worry about the battery draining without us knowing. This battery can be easily charged with a charger that is designed for this kind of battery from Home Depot or Lowe's.



Figure 11: Greenworks Pro 60V battery

3.2.4. Main Battery – SigmasTek 12V 5A Battery

Another option we could use would be to hook 5 of these batteries [17] together to get a 60V 5A power source. This option would be much easier in terms of soldering them together for use, and we could make a housing for them on a piece of plywood. This daisy chain would be a very simple option as well as give us some more torque for our power needs. Figure 12 has the dimensions of 131 millimeters * 196 millimeters * 156 millimeters. So, while some configurations may allow the battery holder above to be used, a plywood or other method of securing the batteries would need to be at most 1000 millimeters long.

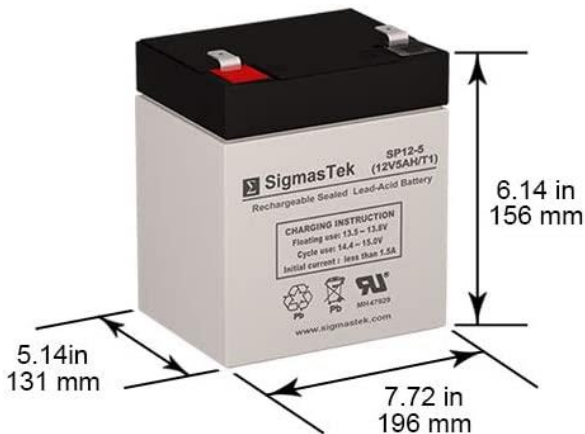


Figure 12: SigmasTek Battery

The only downside to this battery is that there is no measurement on the side of it to show the level of charge still in the battery. There will have to be a separate circuit to help decide how much time the submarine has left to explore before it needs to return to its base. However, this should be a simple circuit to design.

3.2.5. Propeller Batteries – Youme Lithium-on battery

Since the propellers took up so much current by themselves, we decided they needed their own dedicated batteries. One option for those is pictured below in Figure 13. These batteries are 11.1 V and 5.0 Amp-hours. [18] This is perfect, as each motor takes up 2.5 Amp hours, so when both motors are being serviced by this one battery, they add up to 5 Amp hours.

These batteries were made to go in RC helicopters and submarines, so we figured it was somewhere to start. At the full capacity, the speed would be much higher, but at least the motors are waterproof and intended for use on a submarine of our size. When manipulating the current and the total amount of power the propellers are putting out the best way to optimize movement wouldn't be to max throttle all the time so by having the limiting factor be a lack of current the submarine would be able to handle swifter cleaner movements. The benefit to this battery would also be size which is much more comparable than most batteries on the market given the intend need.



Figure 13: Youme Power Lithium-Ion Battery

3.2.6. Propeller Batteries – SafeAMP 12 V

Since the motors required a 12 V battery, we investigated just using a replacement battery for a Fisher Price power wheels car such as the one in Figure 14. This battery supplied 9.6 A, but the main problem here is that this battery is 9.62 pounds, and it would not be conducive to the submarine if it were onboard. The heavier the submarine will be, the more power it will consume to propel it forward, so either we use this battery on shore, or we do not use it at all.



Figure 14: SafeAmp 12V Battery

3.2.7. Battery Selection

Table 5: Main Battery

Battery Brand	Price per Unit	Total Price	Number of Units	Weight (lbs.) total	Volts	Amps
VISET Ebike	\$170	\$170	1	5	36	10
Makita 18V	\$60	\$180	3	4.2	54	5
Greenworks	\$190	\$190	1	5	60	5

We chose the Greenworks 60 V battery, because it supplied the exact amount of voltage and current that we needed, while not being cumbersome to maneuver. This is one unit that is lighter comparative to the others, such as the SafeAmp.

Table 6: Propeller Battery

Battery Brand	Price per Unit	Total Price	Number of Units	Weight (lbs.) total	Volts	Amps
Youme Power Pack	\$38	\$114	3	3.09	11.1	5
SafeAMP 12	\$40	\$40	1	9.62	36/48	9.6

From Table 6 we chose the Youme Power Pack despite their high price point. The lower cost of the batteries in the main battery section above allows more money to be allocated to procuring these batteries. The propeller battery provides exactly the right amount of power for the motor pairs and for the large pump. These batteries are intended for the motors, which require a higher level of current than any other part on the submarine. They also weigh significantly less than the SafeAmp battery, which is important in case the remaining components of the submarine are too heavy, and the inclusion of the main battery makes the submarine become negatively buoyant. The lighter weight would avoid exacerbating the heavy nature of the submarine and would allow it to become buoyant.

3.2.8. After Demo Battery Selection Update

The final battery chosen for the land battery was the Greenworks 60V battery. This battery was chosen for a few reasons, including its post-project utility, easy acquisition, and being more cost effective than the other batteries. While such a battery has no built-in converter from battery to DC power, this was easily rectified by purchasing one from online.

3.3. Speed Controllers

Our original plan was to use voltage regulators to control the speed and direction that the motors propelled the submarine in. However, after some investigation, we found that we cannot regulate the power for the motors, since there is too much current needed. We came to the conclusion that we needed 4 speed controllers for the 4 motors.

Without using speed controllers, there would have to be a special regulator circuit on the PCB. For our purposes right now, there are enough moving parts on the PCB to not tackle this as well. These speed controllers will also function as our navigation. Since there is already such a thing as a speed controller that will be able to limit the current going to the motors via pulse width modulation, then this is a perfect option to run with rather than creating a circuit that will reduce the current. If we regulated the voltage going to the motors, this option would not be very feasible as the current is what determines the strength of the force.

3.3.1. RC Electric Parts 40A Speed Controller

Brushless DC motors offer several advantages over their brush-using counterparts and as such we made sure to get brushless speed controllers for the propeller motors. One type we considered was the RC Electric Parts Brushless Motor controller shown in Figure 15 below. They are said to work with motors that are 6.4V - 16.8V, and because of that, they should work with the ones we have chosen. This electric speed controller is coming with 2-4 lithium polymer cells, and provides a continuous output of 40 amperes. It weighs 48 grams, has a size of 71*35*10.5 millimeters, has minimal heat loss, and has "programmable, super smooth, and accurate linear throttle adjustment" [20].



Figure 15: RC Motor Controller

3.3.2. Opaltool Brushless Controller

These Opaltool Brushless Controller pictured below in Figure 16 was designed to be used for small vehicles such as electric bikes and scooters. The Opaltool speed controller is notable in being able to work for 36V/48V operations [21]. Due to the use of Power over Ethernet, which required us to drop our voltage down to 12V we had to eliminate the Opaltool controller as an option. Note that due to its intended application being for bikes and scooters that the controller will come with several wires that can be used for controlling multiple motors from the same device.

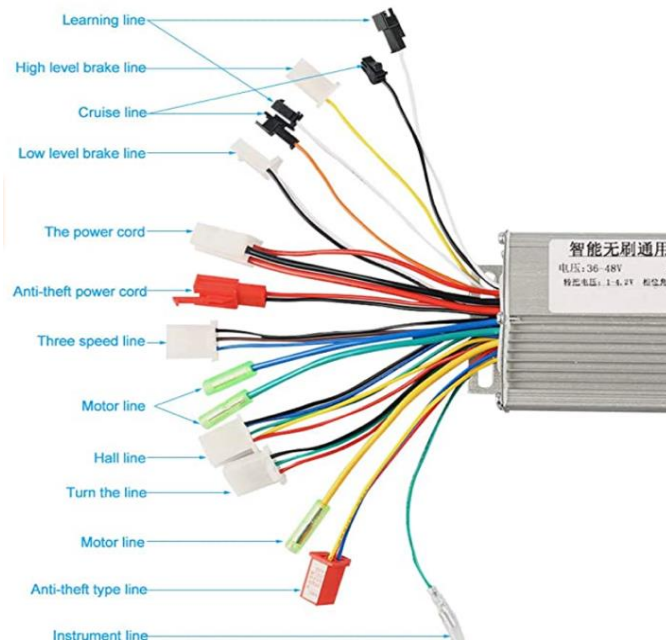


Figure 16: Opaltool Brushless Controller

3.3.3. Speed Controller Selection

Table 7 summarizes the data between the RC Electric and Opaltool speed controllers. It was determined that the Opaltool controller is too complex for our motors. There will be one speed controller paired to each individual motor. The smaller RC Electric controllers are a better fit for our motors. This way there is at least one controller per motor and the Raspberry Pi will be able to provide an individual signal for each motor.

3.3.4. After Demo Speed Controller Update

Instead of the speed controllers mentioned above, we opted to use an h-bridge driver chip. This was significantly cheaper and smaller than the other speed controllers whilst being more reliable to control.

Table 7: Speed controller comparison table

Controller Brand	Price per Unit	Total Price	Number of Units	Volts	Amps	Interface Complexity
RC Electric	\$21.50	\$89.00	4	6.4-16.8	40	Low
Opaltool	\$20	\$80	4	36/48	9.6	High

3.4. Cable Sheathing

Our requirements are for a sheathing to go around the cable to protect it in the water. It would be undesirable for anything to be able to cut this cable and allow water to get inside the cabling. With 48V running through the umbilical cable, any fish nearby would get electrocuted, and this would allow water to get into the submarine flooding it and damaging the electronics. With the sheathing, if something sharp comes along, the goal is that there is another layer there to protect the cable on top of the existing wire insulation. Table 8 provides data on the sheathing types that were considered.

Table 8: Cable Sheathing

Type / Material	Price / foot	Lightweight (Y/N)
Nylon Multifilament Braided	\$0.32	Y
TechFlex Stainless Steel	\$2.37	N
Reflex Braided	\$1.97	N

3.4.1. Nylon Multifilament Braided Sheathing



Figure 17: Nylon Cable Sheathing

The sheathing shown above in Figure 17 best met our requirements, as it was light-weight, durable, and affordable. The 3/8" width of sheathing, costs \$39.99 for 125 feet, shown in Table 8 so the Ethernet cable would fit inside and be well protected. The Nylon Multifilament Braided Sleeve is exceptionally strong and will hold up in almost any application, including under the hood of a vehicle, along the floor, and even outdoors, as it resists UV damage and does not rot or retain moisture. These characteristics make it an excellent choice given our budget.

3.4.2. TechFlex Stainless Steel

The second option we considered was TechFlex stainless-steel sheathing [5]. Some of its characteristics are that it is very sturdy and will hold up in any type of water environment and will not rust. This sheathing will provide superior protection such that no rock or fish could break the umbilical cable causing loss of power and/or data. However, at a cost of \$2.37 per foot seen in Table 8, fifty feet of this sheathing would exceed our budget. See Figure 18 for the sheathing.



Figure 18: Stainless-steel sheathing

3.4.3. Reflex Reflective Sheathing

The third option we considered was a highly reflective braided sheathing shown in Figure 19 that provides abrasion and chemical resistance, and includes the benefit of high visibility, due to its 360-degree reflectivity. However, the Reflex Reflective shielding costs \$147.98 for 75 feet [22]. Since we have no requirement for it to be reflective, we eliminated it from our consideration. Although the fact that it would never get rusty is a great benefit over the stainless steel over the years, the nylon type of sheathing also does not rust and would wear great over the years through the grinding it would do when reeled up for storage.



Figure 19: Reflex Reflective Sheathing

3.4.4. After Demo Sheathing Update

Despite the belief that time would be available for lake or ocean-going testing, this was not the case. As such, the requirement to have sheathing to protect the Ethernet cable between the controller and the submarine was dropped. Upon reflection, sheathing such as the ones above are no guarantee of protection from creatures larger than lake-bound fish, and the coating is thick enough on the purchased Ethernet cable that damage to the internal wiring is unlikely. It is also believed now that adding such sheathing would add extra weight, drag, and cost to the cable with no tangible benefit.

3.5. Headlight

There were several types of lights that we could choose from. We considered a scuba light from Amazon as seen in Figure 20 below. We have deconstructed this light so that we are just using the front housing piece and the light bulb. This light is completely submersible and produces a light beam of 1800 Lumens, so it should be able to light up everything we need it to. Since this flashlight is powered by batteries, we will instead wire it up with our battery instead of the 3 AAA batteries that the housing is intended to hold. We will attach the flashlight bulb and chrome casing to our submarine housing using Marine Weld adhesive,

which will make sure the light is adequately held in place as well as keeping the submarine waterproof.

We went with this headlight due to its overall specifications. From our searches we found that this headlight was one of the smaller devices available and was easier to integrate into our design. This is partially due to the fact that we can take most of it apart, and only use the pieces that we need for it to function, for example our ability to take off the back and wire it to the battery instead of having AAA batteries installed in it. It also was not too much of an increase on our overall power consumption limits. All of this considered we found that this was our best option available for our design and chose to integrate it into the plans for our submarine. This lamp has three modes including two brightness levels and a strobe feature, which will be able to be controlled by pulse width modulation (PWM) through our onboard computer.



Figure 20: Example of flashlight.

3.5.1. After Demo Headlight Update

As mentioned before, the goal was to have adjustable headlights to give the user flexibility while exploring darker environments. Despite the headlights seeming like strong candidates as they are whole assemblies as opposed to just LED bulbs, it was quickly discovered that a Pulse Width Modulated signal could not be used to control them. In particular, the application of ANY power to the flashlight changed the mode that they were on, meaning that performance would be unpredictable. Additionally, the underwater protection came primarily from the casing, meaning that disassembling the flashlight rendered it unusable.

The replacements chosen were the CREE C513A-WSS-CY0Z0341 five millimeter LEDs. As these were standard LEDs, they were chosen for their significantly cheaper price, small profile, direct drivability, electrical compatibility with the existing submarine PCB, as well as the fair trade between millicandela rating and viewing angle. These chosen replacements worked well as can be seen here in Figure 21 and Figure 22.



Figure 21: Bubbles' light cone (Created by the Authors)

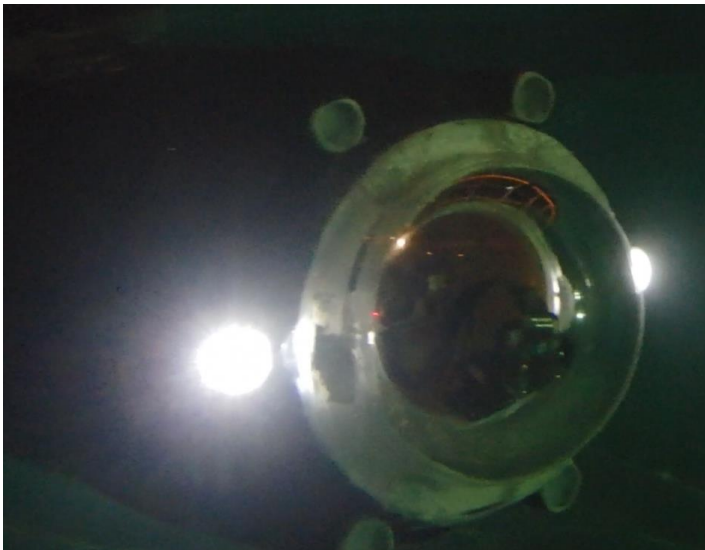


Figure 22: Headlights as seen from front (Created by the Authors)

3.6. Submarine Motors

The propellers are the component used to change the direction and speed of the submarine. Propellers can be activated in tandem and in the same direction for power, or with different rotations or speeds to change direction. After we discovered what our motors needed to accomplish, we began searching for the right ones for the job. We looked at several motors to propel this submarine such as the following:

- Lichifit RV Jet Submarine Underwater Motors from Amazon 2 pack
- Liuqingwind 12-24 20 A brushless motor 2 pack

An H-bridge setup was not initially considered despite its ease of implementation due to concerns about manually implementing speed controls to the motors.

3.6.1. Lichifit Underwater Motors

The Lichifit motors are provided as a pair from Amazon and each set includes propellers. For testing have they were arranged as shown in Figure 23. The propellers are of opposing angles of attack. This means that the opposing angles of attack would cause the water to flow in opposite directions. It will be necessary to compensate for this by connecting the motors in opposing polarities.

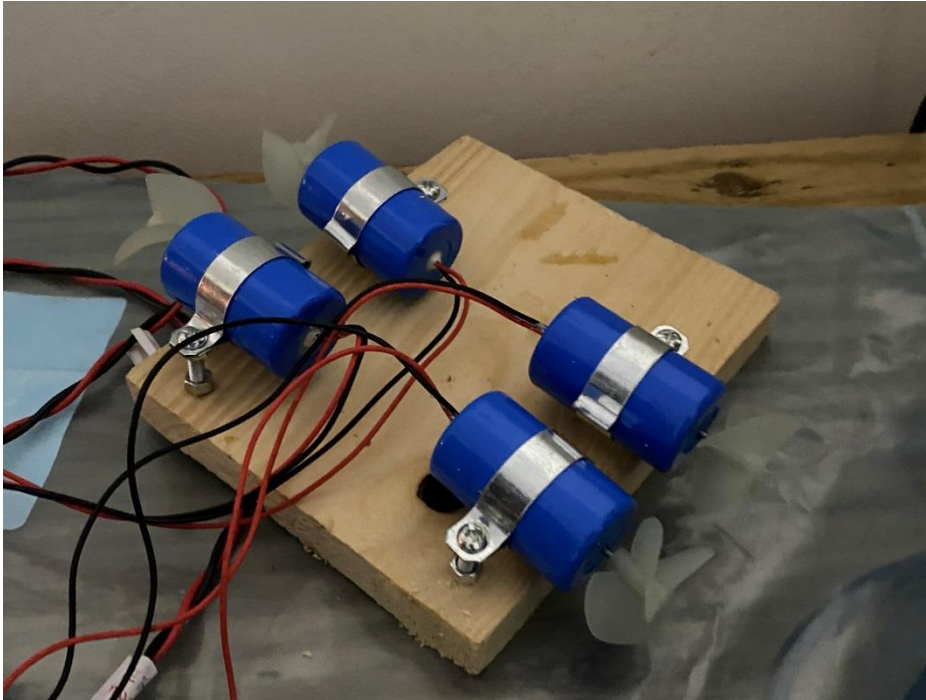


Figure 23: Lichifit underwater motors, with propellers (Created by the Authors)

These motors are quite small, so we thought about using two sets of these motors, for a total of four motors. Assuming one looked at the aft of the submarine with the umbilical cord and internal components such as the camera facing right side up, they would be placed at the 12 o'clock, 3 o'clock, 6 o'clock, and 9 o'clock positions. This way, when we want our submarine to go down, we turn off the voltage to all except the top motor; when aiming upwards, we only turn voltage on for the bottom motor, and the same for the sides. When throttling full speed ahead, all motors will be activated. This will also be the case when going in reverse.

Then, we decided to think about how to control our navigation using these motors. We decided that we would need to be able to control how much voltage is going to each motor. For example, when we want the submarine to turn to the left, more voltage needs to be applied to the motor on the right, which will cause

more of a thrust on the right side and turn the submarine to the left. To help with this issue, we thought about using speed controllers.

Since these motors have brushes and are not brushless motors, we determined this method of navigation might be harder. While looking for the speed controllers, we found that they work much better with brushless motors than with motors that have brushes. That led us to research brushless motors instead.

As it turns out, the brushless speed controllers will work with our motors, since there will be little current flowing through. The brushes create drag, which makes it harder to use with the speed controllers, but since the motors will not be used at full force, the type of speed controller we have will work.

3.6.2. Liuqingwind 12-24V Brushless Motors

This set of brushless motors frequently appeared [24] whenever we tried to research different waterproof motors, so we investigated them. As brushless motors, they produce less (if any) electromagnetic interference. They require more electrical power, but these motors are larger coming with 3-inch propellers, and would be more powerful as a result. These motors are more aesthetically pleasing than the Lichifit motors, and can be more easily integrated to our submarine body. Another positive aspect of these motors is the guards around them which prevent direct damage due to hitting rocks.

However, the blades are composed of nylon, and when they are rotating at high speed, pose a risk to the surrounding wildlife by being able to suck them in. An additional downside is that the motors require three-phase drive which is more complicated to design especially given the limited amount of general purpose input and output lines. The most serious downside is that they cannot be operated completely submerged without access to a supply of air, which disqualifies their use in our submarine.



Figure 24: Liuqingwind Brushless Motors

Although these motors in Figure 24 had some good points, their size and cost were the deciding factors in not using this set of motors.

3.6.3. Submarine Motors Selection

As seen in Table 9 below, we chose the Lichifit motors for use on our submarine design. Both motors required comparable power, but there were issues with the Liuqingwind motors in securing them to our hull. The Lichifit motors require significantly less power and they come at a lower price than the Liuqingwind motors.

Table 9: Submarine Motors

Motor Brand	Price per Unit	Total Price	Number of Units	Volts	Amps	Can operate underwater
Lichifit	\$13.00	\$51.00	4	7.4	15-30	Yes
Liuqingwind	\$20.50	\$41.00	2	12-24	20	No

3.7. Camera Selection

The ability to see where the submarine is traveling and the environment the submarine travels in is a top-level requirement, and the choice of this part will greatly impact the performance of the vehicle. Part selection must be conducted to allow for easy access of captured video, and the quick turnaround of its frames via the chosen transmission method. The choice of camera may not have the ability to record, instead deferring this ability to the on-board computer. The large breadth of camera choice means that time must be spent selecting the most appropriate camera. The below sections cover specific kinds of camera technologies, as well as potential part selections. A summary of the important features is shown in Table 10.

3.7.1. Monoscopic Video

Monoscopic video is the use of a single camera for capturing image streams and is the most prolific vision system among underwater ROVs. The reason for its widespread use is the ease of implementation, requiring the access and transmission of only one video stream resulting in less data to be sent. Viewing of the outside world is dependent on the orientation of the submarine and maintaining vision on a point of interest requires the operator to be aware of such orientation.

3.7.2. Stereoscopic Video

Stereoscopic vision systems use two cameras instead of one and are often found in commercial applications. Like the monoscopic video, the operator must be aware of the orientation of the submarine and the surrounding environment. Stereoscopic vision systems provide two advantages over their single-camera counterparts: redundancy and additional depth of field information. Acquiring this information is a trivial problem in computer vision and would be one method of providing a virtual reality experience should development time allow.

3.7.3. Rotational Abilities

While a fixed-view camera system would simplify the control scheme of the ROV, this comes at the cost of minimizing what can be seen in the environment. Should the submarine be held steady, it is desirable to allow the user the ability to rotate the camera to see the environment immediately surrounding the sub, or to track a moving fish. Having a rotating camera would also improve the utility of a VR system, allowing the user to look around their environment. A VR system combined with a rotating camera may also be computationally simpler, as opposed to the equirectangular projection methods used by omnidirectional cameras. Having a rotating camera would require additional wiring on both the submarine and the controller, and the camera must be placed on the submarine in an optimal location.

One method for rotation would be to mount a camera on a rotating platform, which would allow either 80 degrees of rotation if mounted directly at the front, or 360 degrees if mounted on top. Some commercial ROVs have gimbal mounted cameras, allowing both rotation and translation of the camera. This option allows the greatest freedom of movement, at the cost of mechanical complexity and potential balance issues. Even if the gimbal arm were made of a light material, the additional mass would cause the submarine to list to the side of the submarine with the arm, requiring additional work from the buoyancy system to counteract and hold steady.

3.7.4. Go-Pro Hero Series

A primary motivator in our design of the submarine was to have a way to swap out models of camera used by the operator and could connect to the on-board computer via USB and micro-HDMI ports. The Go Pro Hero series of action cameras are advertised as being lightweight, reliable, high resolution waterproof cameras. This along with a potentially pre-packaged streaming ability, and because a team member already has access to one, make the Go-Pro alluring on the surface.

However, livestreaming is only officially supported on the Hero 8 via wire, and for older models requires use of an app or their subscription service. The main body of knowledge for using older models of the Go-Pro Hero series lies with other customers attempting to access video like we are. One proposed way to access the video is to use an Elgato cam link, which is a micro-HDMI to USB-C

converter with built in streaming support, but this is expensive for us, being in the \$110-\$150 range. Another alternative is to strip down the Go-Pro camera and directly access the circuit board, which is a common technique for cameras on do-it-yourself submarines. This is a risky proposition, as damaging a vital pin could result in replacing the camera, which is often sold at \$100-\$200. Replacement could also be required if the submarine hull is breached or if the submarine becomes stuck at the bottom of a body of water. To avoid this, a built for purpose imaging sensor or alternative action camera could be used instead.

3.7.5. Alternative Action Cameras

One alternative action camera is the Campark 4K Action Camera. Touting the ability to capture 16-megapixel photos, a 170-degree view with its wide-angle lens, and a case that can survive at a depth of 30 meters underwater, this camera can serve as a viable alternative to the more expensive GoPro. Most importantly, the action camera supports the ability to directly access the video like a webcam, which is an important consideration. However, there is concern about the camera once purchased, as user debate suggests that the performance varies between cameras of the same model. For example, users suggest that the camera can overheat within five minutes, loss of power may reset the settings, and the picture quality can be grainy or blurry at times.

3.7.6. USB Webcams

Since interchangeability of cameras is a primary design goal, one option would be to use a USB webcam connected to the on-board computer through a waterproof USB port. As the Universal Serial Bus is a de facto standard for connecting devices to computers, pursuing this option would simplify powering for and interaction with the camera significantly. Additionally, most USB cameras have small profiles, which would allow for a reduction in the overall size of the sub.

One possible model for this option is the Vonter 1080p webcam, which has a head that can be rotated 360 degrees horizontally and tilted 60 degrees up and down. However, it comes with some major downsides such as its lower definition resolution and its use of USB 2.0 may prove to be a bottleneck in reception speed. Another option includes DEPSTECH webcam, capable of automatic light correction for its 2560 x 1440 resolution, 86-degree view. It also can be rotated 360 degrees horizontally, but this range of motion and lower cost of \$35 comes with the tradeoff of a larger physical profile, which would make the size of the submarine larger as well.

3.7.7. Usage of Camera Modules

There are some applications that may require the use of camera modules as opposed to traditional cameras. Full color imaging sensors would be cheaper than their full camera counterparts, and their wires would allow direct access to images, as opposed to interacting programmatically with them. Using camera modules instead of full-sized cameras would also reduce the amount of space

used on the submarine. Some applications may also require the use of special low-light camera modules, such as if the sunshine from above is not enough or if the lights fail. Other applications may require infrared sensors, allowing the user to see the temperatures of the environment and its inhabitants, though this depends on the requirements of the operator. These additional imaging sensors will be implemented if time allows.

3.7.8. Raspberry Pi OV5647

Coming in at \$17, the Raspberry Pi OV5647 wide angle camera module is advertised to come with a fisheye lens. Compatible with all Raspberry Pi models, this module is significantly smaller than its Sony counterpart, and can be plugged in and directly interpreted by Raspberry Pis. However, with smaller static image resolutions, smaller video resolutions, max 1080p at 30fps video, and barrel distortion that must be corrected, the Raspberry Pi should only be selected if budgetary constraints are of serious concern. Other versions are sold with even smaller cameras while maintaining the resolution, and are sold for \$9, which makes it a good budget camera.

3.7.9. Sony IMX477

The Sony IMX477 is a “HQ camera module which adopts the IMX477R sensor... compatible with Raspberry Pi Compute Module and NVIDIA Jetson Nano”. It has 12.3 MP and offers improved low-light performance over their IMX219 counterparts. Also capable of capturing a 4056 x 3040 image at 60 frames per second, it carries this information via a 4-lane MIPI output interface. It’s also capable of recording a 1080p video at 120 fps assuming a 2-lane MIPI setup and some versions have a MIPI to USB converter, making integration easy. For its webcam style access and significantly higher resolutions, a \$40 price tag makes this a fine choice and allows for more of the budget to be spent on hull reinforcement and sealant.

3.7.10. Adafruit NTSC Serial Video Camera

The Adafruit serial video camera is a camera module that outputs NTSC video transmitted over a TTL serial link. Compared to other camera modules it is advertised to come with “manually adjustable focus, auto-white-balance, auto-brightness and auto-contrast... as well as motion detection-built in.” The camera module can be used using two digital pins or a dedicated TTL serial port and can be interacted with at speeds between 38400 to 115200 baud. Snapshots can also be taken of that video in the form of pre-compressed JPEG images, making them easy to store. The main draws are its use of serial communication, motion detection capabilities, and Arduino libraries, but \$40 for less resolution than other camera modules is significant.

3.7.11. ELP 2.1mm USB Camera Module

With a price tag of \$46, the 2.1mm ELP camera module is capable of wide-angle video capture with its 1/6.86 centimeter optical sensor and transmitting it via USB

back to the on-board computer. It can capture 1080p video at 30 fps, and 720p at 60 fps. Unlike most cameras, the ELP is advertised with contrast, color saturation, and brightness configurability, much like traditional full-sized cameras. This is a surprising feature, as most webcams or imaging sensors provide no way to adjust the color grading. This option allows the tuning of the camera to be more representative of the brightness of colors of the underwater environment. The lighter weight of the camera also helps reduce the weight that the ballast system must counteract in order to maintain a steady depth in the water.

3.7.12. Charmed Labs Pixy2 CMUCam5

The Pixy2 CMUCam5 smart vision sensor is notable for its object tracking applications. This is because the vision processing is offloaded from the main computer its own processor. The Pixy2 is a plug-and-play system that can “learn to detect objects ... just by pressing a button”, with a controllable amount of data able to be sent from the sensor via USB, serial UART, SPI, I²C, digital out, or analog out. The system is also more flexible in detection due to using hue and saturation, as opposed to regular RGB, and can process 1296 x 976 images at 60 fps. While \$70 is expensive for pursuing stretch goals, the variety of communication methods and the offloading of work from the on-board computer would enhance the experience for viewing underwater environments beyond our current working goals.

3.7.13. Camera Comparisons

Providing a video system that allows for high-definition footage, rapid transmission of and easy access to video frames, as well as ease of use is important for fulfilling the requirements for underwater exploration. Rapid video transmission includes the speed that video frames can be encoded into a packet and decoded at the hand-held controller, and the more data that needs to be sent the more preprocessing time is required before sending it from the camera. The use of a pan and tilt mechanism requires it to be easily controllable from the on-board computer, and that the cables required for the camera are long enough to reach the computer without snagging. Another aspect to consider is the support for the chosen device whether it is official from the device manufacturer or from the community that grew around using it. Such resources that could be used include wikis of information, tutorials, sample codes, and signaling diagrams as required. The amount of such support must also be determined on a per camera basis, and strong support can offset the difficulty of implementing a camera into the design.

The final selection for a camera was ultimately dependent on determining if a low-cost pan and tilt mechanism existed, irrespective of the camera being either monoscopic or stereoscopic. Monoscopic systems have much less data storage requirements compared to omnidirectional or even stereoscopic vision systems.

3.7.14. Final Camera Selection

The camera that we have chosen to use is the Raspberry Pi OV5647 module as seen in Figure 25. This is primarily because of its low price point, high image sensor resolution, as well as its compatibility with the other chosen systems. In particular, the camera can stream 1080p at 30fps sending images taken by its 3280*2464-pixel resolution sensor. The use of a Raspberry Pi for the on-board computer makes interfacing with the camera very easy, as there is a dedicated MIPI-CSI connector on board the Pi. The use of a single view camera minimizes the amount of data to be stored, but when combined with the motorized pan-tilt mechanism, provides increased user control. This is significant, as the benefits of omni-directional and gimbal-arm based cameras have been achieved without the computational cost or significant mechanical design. The pan-tilt mechanism is shown in Figure 28, with the way that the camera connects to the Raspberry Pi being shown in Figure 26.

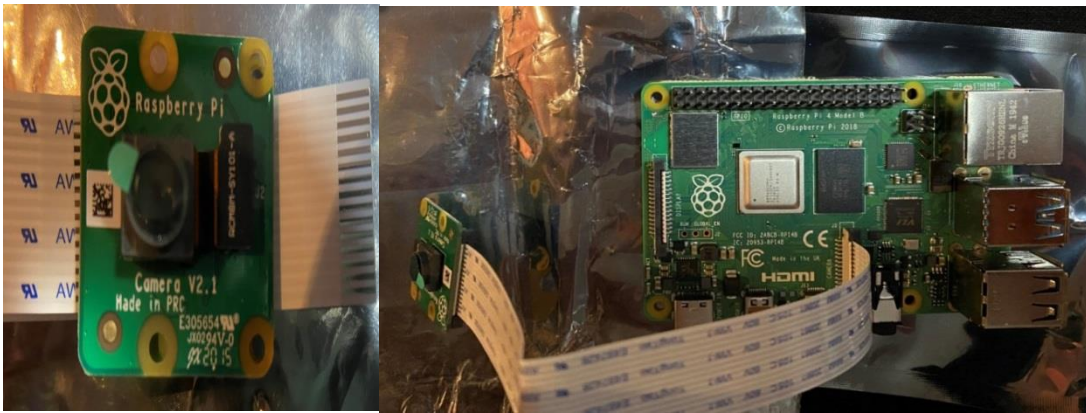


Figure 25: (Left) Raspberry Pi Camera V2.1 Module (Created by the Authors)

Figure 26: (Right) Camera Module and Raspberry Pi Connected (Created by the Authors)

3.7.15. After Demo Camera Update

Figure 27 below shows the camera mounted on the pan/tilt mechanism along with a picture taken from the bottom of the testing pool. Note that the images appear much cleaner in real life, and that the picture of Jacob waving on the right is taken under low-light conditions on a separate mobile device.



Figure 27: Camera in dome and picture taken with camera in dome (Created by the Authors)

Table 10: Camera Feature Comparison

Model	Cost (\$)	Size	Video Modes	Sensor Resolution	FOV (degrees)	Library Support	Ease of Interface
Raspberry Camera Module V2 with OV5647 sensor (includes ribbon cable)	\$25	25 x 24 x 9 mm	1080p30 720p60 480p60/90	3280 x 2464 pixels	62 H x 49 V	Yes (in Linux)	SUPER EASY: Included ribbon cable plugs into dedicated connector on the Raspberry Pi
Go-Pro Hero 7	\$250 Note 1	62 x 45 x 33 mm	Dozens of modes 720p 240FPS 4K 60 FPS	Not provided	122 H x 94 V	None provided Note 6	RISKY: Requires disassembly to access internal PCB, or use Elgato Cam Link
DEPSTECH 2K Office Webcam	\$35		2560x1440p	2560 x 1440 pixels	86 H		EASY: USB
Sony IMX477	\$40 Note 4	7.6 x 5.5 mm Note 2	1080p at 60 FPS	4056 x 3040 pixels	Note 4		MEDIUM: Two-wire serial communication (CSI-2)
Adafruit NTSC Serial Video Camera	\$40	32 x 32 mm	480p at 30 FPS	640 x 480 pixels	60 H	Yes, Arduino libraries	EASY: 3.3V TTL serial link at 38400 to 115200 baud (Note 3)
ELP-USB Camera Module	\$46	TBD	Eight modes, 240p at 120 FPS to 1080 at 30 FPS	1920 x 1080 pixels	170 H	Circuit-Python and Arduino libraries	EASY: USB
Charmed Labs Pixy2	\$70	1.5 x 1.7 x 0.6 inches	Note 5	1296 x 976 pixels	60 H x 40 V	Open-source libraries for Raspberry Pi	SUPER EASY: Included ribbon cable plugs into dedicated connector on the Raspberry Pi
Charmed Labs CMUCam5 (an older model)	\$70	2.1 x 2.0 x 1.4 inches		1296 x 800 pixels	75 H x 47 V	supports C and Python	EASY: USB, serial UART, SPI, I2C

Note 1: Elgato Cam Link requires a micro-HDMI to USB-C converter with built in streaming support costing \$100-\$150.

Note 2: This part is a 92 pin LGA that would require being given its own PCB.

Note 3: Datasheet provided gives example communication sequences.

Note 4: FOV depends on lens – purchased separately.

Note 5: This is a vision sensor for detection of objects; not really a camera in the traditional sense.

Note 6: Hobbyist-developed libraries of varying quality may be available.

3.8. Motorized Tripod Mounts

Stereo vision systems and omnidirectional cameras come with a few problems that make them undesirable to pursue. For example, the need to double camera support in the case of stereo vision, such as for transmission and for storage. If VR is pursued, there is also the need to be able to map them to each eye. In terms of omnidirectional cameras, the barrel distortion of the view is required to be mapped to an equirectangular projection for storage and transmission, which risks degradation of image quality at the polar regions. If a motorized tripod mount was to be included as part of our defined stretch goals for VR, the user would be able to look up and down, as well as side to side.

3.8.1. Zifon YT-260

One system that was examined was the Zifon YT-260 motorized tripod mount. The motor can rotate at least 230 degrees horizontally and vertically, with a pan speed of 2.5 rotations per minute, and a tilt speed of 1.5 rotations per minute. It can smoothly support a camera that weighs 260 grams, but any heavier and it may slow down or break. The problem with the tripod is that it's controlled by a remote and would need to be bypassed to be controlled by the on-board computer. One way to handle this would be the use of pulse-width modulated signals going into the controller board, and thus taking it apart is needed to gain access. Another way to do this would be to have an internal transmitter to transmit commands to the rotating platform.

3.8.2. Waveshare Pan-Tilt HAT

While not called a tripod mount, another item considered was the Waveshare Pan-Tilt HAT. It is a two degree of freedom motorized kit that is controlled via pulse-width modulated signals on an I2C bus. It also comes with an ambient light sensor which can be interacted with via I2C. The HAT is moved via the Adafruit PCA9685 servo driver, which can receive signals on its 16 channels with a 12-bit resolution. As this pan-tilt kit is meant to be controlled by a computer, unlike the Zifon-YT which is meant to be controlled by a remote, there is official support in

the form of a wiki. This wiki contains multiple code examples, libraries, and Linux support due to being made for use with a Raspberry Pi. Also, in its favor is its much cheaper price for a fair rotation speed - found by examining the TowerPro SG-90 servo motor - of 600 degrees per second (1.67 rotations per second). All this together makes it worth choosing for the mount.

3.8.3. SparkFun ROB-14391

Yet another possibility is the significantly cheaper SparkFun pan/tilt bracket kit. With an average price of \$7, this pan/tilt kit is as simplistic as possible, as this does away with the I2C interface used by the Waveshare HAT, instead plugging directly into the Raspberry Pi. Due to its simplistic nature, data on the components is minimal, although it is supported by the manufacturer with instructions on interfacing to the Pi. Interacting with the pan/tilt mechanism is based on code from their GitHub page, with the assumption that the Raspberry Pi OS is not graphically installed with an IDE. Different instructions exist if the on-board controller was an Arduino.

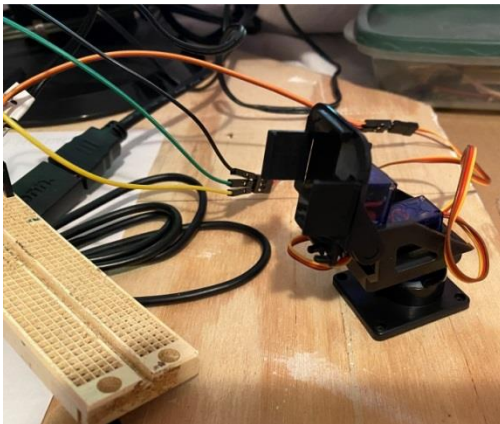


Figure 28: The SparkFun ROB-14391 Pan-Tilt Mechanism (Created by the Authors)

Mechanism	Cost	Rotation Angles	Rotation Speed	Support
Zifon YT-260	52*	230 pan 60 tilt	2.5 r/min 1.5 r/min	Community
Waveshare Pan-Tilt HAT	22	180 pan 100 tilt	1.67 rotations per minute	Official
SparkFun ROB-14391	7	Same as Waveshare	Same as Waveshare	Official and Community

*Price is an average.

Table 11: Motorized Pan-Tilt Comparison

As can be seen from Figure 28, we chose to go with the SparkFun ROB-14391. A primary reason for this choice was the very low cost of the item compared to other possible selections shown in Table 11. This means that if needed, the part can be easily replaced such as if the mechanism got stuck.

3.9. Video Transmission Methods

As important as the choice of camera, number of cameras used, or rotational ability is the choice of video transmission method. This is a choice that must be made both external and internal to the submarine. Like the choice of vision system, the choice of this as part of the camera selection will greatly impact the performance of the vehicle. A good choice will facilitate rapid transmission of the video data and maintain the color and resolution from the camera. The below sections cover specific kinds of transmission technologies and are summarized below in Table 12.

3.9.1. HDMI

The High-Definition Multimedia Interface is an interface specification that has existed since 2002 and was built on top of standards published by the Consumer Electronics Association and Electronic Industries Alliance, as well as those from the Video Electronics Standards Association. All HDMI compliant devices must implement the sRGB color space, which allocates 8 bits per color component for backwards compatibility reasons, but newer versions also allow the use of various color spaces and chroma subsamplings such as allocating 16 bits of color per component. HDMI interfaces are found on several common electronic devices such as televisions, computers, and most importantly for us: cameras. Despite no maximum length specified within the HDMI specifications, significant signal degradation occurs past 13 meters, and is why it is rare to find them outside of online retailers. This length limitation and the general stiffness of their cables make it impractical to use for the umbilical cord, but for internal connections such as from the camera to the on-board computer, a cable such as a mini-HDMI cable would be used. No bottleneck would exist between the camera and the on-board computer, as even HDMI 1.0 can transfer 1080p footage at 3.96 GBps.

3.9.2. USB

The Universal Serial Bus (USB) is an industry standard for communicating between devices and a host controller. Like HDMI, it is commonly used on devices such as phones, computers, and cameras. While it has largely replaced serial ports, a USB port can still be used as a serial port should it need to. USB cables are specified to be 2-5 meters in length, and thus would be used inside of the submarine between the camera and the on-board computer. A multitude of modern devices use USB-C, although devices such as cameras may use the smaller variants such as the mini-USB or micro-USB connectors. USB 3.0 connectors can transfer data with a maximum bandwidth of 5 GBps. Unlike HDMI, USB has the ability to interact with other devices through USB ports, making it more general and able to be used throughout the sub. Additionally, because USB can carry power, some small devices can be powered through a USB cable, such as the cameras. Video can also be transmitted along this same

cable, allowing for the possibility of reducing the amount of wiring required for the camera.

3.9.3. MIPI CSI-2

The Mobile Industry Processor Interface (MIPI) Alliance created the MIPI Camera Serial Interface 2 and describes it as “a widely adopted, simple, high-speed protocol primarily intended for point-to-point image and video transmission”. It is noted as able to support a large range of high-resolution photography, from 1080p to 8K. The interface has been used to connect devices for IoT applications as well as those used for virtual reality projects. The protocol is fast and lane-scalable, with “up to 41.1 GBps using a three-lane (nine-wire) MIPI C-PHY v2.0 interface, or 18 GBps using four-lane (ten-wire) MIPI D-PHY v2.5 interface”. C-PHY and D-PHY represent the physical layer in the UniPro protocol stack used by members of the MIPI alliance. While the actual specification of CSI-2 is available only to MIPI alliance members, using products that implement the protocol is not. Some on-board computers such as the Raspberry Pi can directly interact with cameras that implement the protocol, meaning that no adapter is required.

3.9.4. Ethernet Cabling

There are several categories of Ethernet cabling, with variants used today including Cat 5e, Cat 6, Cat 6a, Cat 7, and Cat 8. While all use the RJ-45 connector, they differ primarily in their supported bandwidth, maximum data rate, and shielding. Cat 5 operates works with 100 MHz and a transfer speed up to 1000 MBps, whilst Cat 8 uses a 2 GHz bandwidth for moving data at up to 40 GBps. There are cases where the differences in cost are negligible between Cat 7 and Cat 8 cable, with the average cost being \$20 for a 15.24m long cable. Cat 6 cable however, costs \$13 for the same length, and a maximum data rate of 10 GBps would be more than sufficient for our needs. The Raspberry Pi 4B, chosen for its Gigabit Ethernet port, would be able to handle the high speeds provided by the Cat 6, Cat 7, and Cat 8 cables. In terms of length, the maximum length that a Cat 7 can be is 100m whilst supporting 10 GBps.

3.9.5. Wi-Fi

Another possible transmission method is via Wi-Fi, as most routers have an outdoor range of 91.4m. While Wi-Fi transmission through water, or between water and air is poor, transmission from a buoy to the operator through open air is the ideal scenario for Wi-Fi. By having a cable transmit from the submarine to the buoy, and having that signal be sent via Wi-Fi, the controller is no longer required to be attached to the submarine. This would make it possible for the operator to relocate, and for the submarine to travel farther distances. The ability for the operator to move could allow them to seek shelter in bad weather conditions, while still able to control the submarine. Decoupling the controller from the submarine does however risk the loss of the craft, as should the rope to the buoy be lost, the submarine will be dragged along with it unless the motors are powerful enough.

3.9.6. RS-422

If none of the above methods provided suitable transmission distances or wire flexibility, it was determined that a custom umbilical cable would have to be designed with thinner marine-grade wire. Recommended Standard 422 was examined as a suitable standard to use due to the small number of required wires, its similarity to RS-232 serial communication, as well as its maximum range of 1500 meters. A full duplex, point-to-point technical standard created by the Electronic Industries Alliance, it's also notable for its 10 MBps transmission speed, which is suitable for cameras that have resolutions of 1080p and below. Streaming of 1080p footage requires a transmission rate between 5.6 MBps and 7.4 MBps, meaning that the remaining bandwidth can be allocated for information like sensor data, such as from the buoyancy control system, or commands coming in from the hand-held controller.

Table 12: Transmission Medium Choices

Method	Application	Max Range	Max Bitrate	Flexibility	Interface Difficulty
HDMI	Internal	13 m	3.96 GBps	Low	Low/ Medium
USB	Internal	5 m	5 GBps	Medium	Low
MIPI CSI-2	Internal	15 m Note 1	11.6 GBps (single-lane)	High	Medium
Full Ethernet	External	100 m	10 GBps (Cat 7)	Medium	Low
Partial Wi-Fi	Internal and External	191.4m	1.3 GBps (5 GHz)	Medium (Ethernet)	High
RS-422	External	1500 m	7.4 MBps	Low or High (Material Dependent)	Medium

Note 1: This speed is achieved via the use of the Texas Instruments Flat Panel Display Link III interface and is mainly used for automotive applications. Typical use case of MIPI CSI-2 is actually 30 cm due to its use in mobile devices.

3.9.7. Choice of transmission method

For the choice of internal transmission method, MIPI CSI-2 will be used in a single lane setup. This is because it is the interface that the Raspberry Pi OV5647 camera uses to connect to the on-board computer. The smaller cable it has will be extended out another 30 centimeters to prevent it from becoming tangled with the pan and tilt motor. The longer cable would also allow for a greater range of placement for the pan/tilt mechanism independent of the Raspberry Pi 4B's placement. The Raspberry Pi 4B also supports two MIPI CSI-2 devices, so besides the one camera, additional devices could be added that use this method of communication.

For the external transmission method, an Ethernet cable will be used due to its high speed and greater cable flexibility - an important property when rounding corners and towing long cables. Ethernet cables are also a good choice because they are a widely available, high quality, inexpensive cable to implement communication and power transmission.

3.10. Buoyancy Control

One of the most important parts of our submarine is its ability to sink and float underwater so that it can be used to explore different areas with ease. This section is dedicated to the research put into deciding the best possible ballast system that would allow us to manipulate our submarine's depth accurately and easily.

A System to allow addition or removal of ballast water is integral to our design because without it we would simply not be able to dive lower than the surface of the water. We had quite a few ideas on how to efficiently integrate a ballast system into our design getting inspiration from various methods employed on other remote-controlled submarines, as well as looking at designs used by modern submarines. We had four initial ideas we liked the most: a double hull ballast, a fillable syringe ballast, a gas ballast, and a pump operated ballast.

3.10.1. Filling Double Hull

A fillable double hull is the system most modern submarines use today. There is one interior hull that stays dry internally and this is where most people would be located, and there is a second, exterior, hull that can be filled or emptied internally. Having this system, we would be able to loosely control how much water we fill into the submarine to change its buoyancy allowing it to sink or float.

A main problem we encountered with this idea is that we would have to make a much more complex design with multiple compartments to keep our electronic parts dry, while still having enough space for water. We also would need to have a more complex design with water pumps to bring water in, as well as an air tube coming from land to bring air into the system allowing it to float. This would increase costs overall because we would then need an air pressurizer so that we could use airflow into the submarine to push water out.

Using the double hull system, the volume of our added ballast is entirely dependent on how large our submarine's interior volume is and it would also be a bit less accurate because we would not be able to easily measure how much water flows in from the valves per second, or even when the system is at full capacity. We would also have to intentionally sacrifice about half of our ballast space for holding the electronics, as well as us having to make sure that the weight of the submarine is balanced as it fills so that it would not tip up and down as well as spinning over which would have a big impact on the submarine's performance.

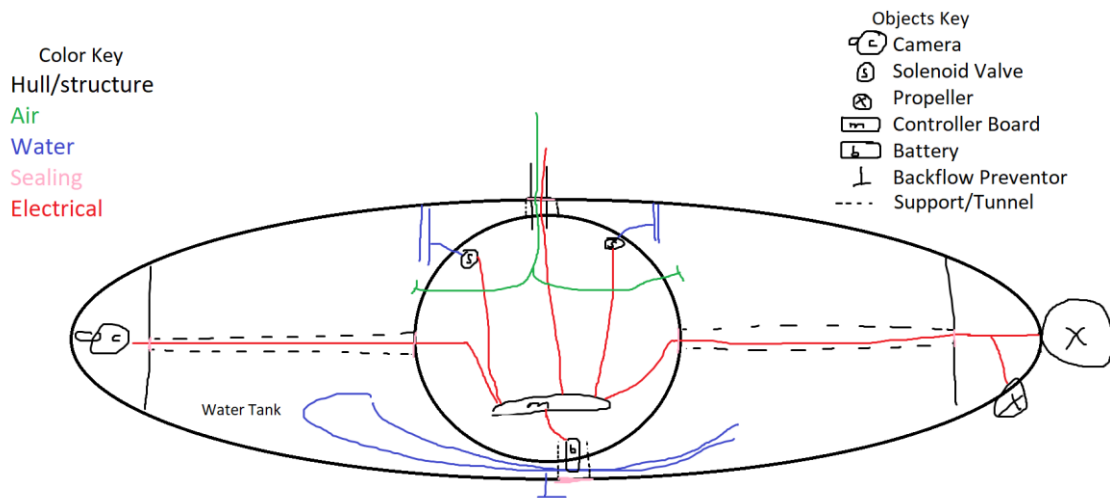


Figure 29: Double Hull Plan (Created by the Authors)

As seen in Figure 29 there would be two intakes for water, ensuring it fills evenly, and an output on the bottom for the water to get pushed out of when we force air in through the umbilical cord and air pump on land. Our three dry sections of the hull would have to be very thought out because we would need to keep the submarine balanced whether it is full of water or empty to prevent tipping. We would also have to have a bridge across the sections for our wires to go through.

3.10.2. Syringe Ballast

A syringe ballast system would be like the original double hull system though it would require less complicated parts to operate. The basic idea of this system is that we would have multiple syringes inside our hull with their needles sticking out the sides. Using a linear actuator, we would be able to push or pull the

plungers allowing us to bring water into or out of the barrel, increasing or reducing our buoyancy. All this system would require are a few syringes, linear actuators, and proper sealing around the needle to ensure no water leaks into the hull.



Figure 30: 60 mL Syringe

For this system we might use four 60 mL syringes, Figure 30, as seen in Figure 30, allowing us to reach a total of 240 mL of water added into the system. Our design to give us linear motion would be a motor with a 4–6-inch bolt attached to it, and on the bolt, we would have a nut that is attached to a circular plate. Activating the motor will spin the screw pushing the nut and plate up or down the bolt and attached to the plate would be the plungers on our four syringes so that when the plate moves it would pull the plungers allowing water in, or push the plunger forcing water out.

A different option that we had was to use two 150 mL syringes [26] as seen in Figure 31, giving us a larger ballast size of 300 mL of water in the system. This would be done using a similar linear motion motor, though this one would have to be 6-8 inches long instead of 4-6 as the 150 mL syringes have larger plungers.

The main difference between using different size syringes would be that you can choose between either getting a larger amount of volume or having a more balanced distribution of the weight. With multiple smaller syringes we are able to place them strategically so that they fill at an equal pace and don't cause the submarine to tilt to one side or another. With a larger syringe you can take on more water ballast and let the submarine sink to greater depths.

We also had to consider the overall desired size of the submarine. The bigger syringes we could use would mean that we would have to get a larger submarine to accommodate both the electronics needed as well as the syringe for ballast. This can be a bit of a double-edged sword because a larger submarine means that we will need more ballast weight to get the submarine to sink, or more initial weight to make the submarine neutrally buoyant. If we have a smaller submarine,

we can use less ballast but will have less space to fit all the electronics that we need to operate the submarine.



Figure 31: 150 mL Syringe

Using a sensor on the end of the syringe's plunger we would be able to accurately tell when the syringes are fully extended, and since we would be able to accurately know the speed of the motor, we would also be able to tell how much water we fill the syringes with when they are being used. This design also allows us to put the syringes in specified spots so that we can ensure the submarine is balanced as it fills with water.

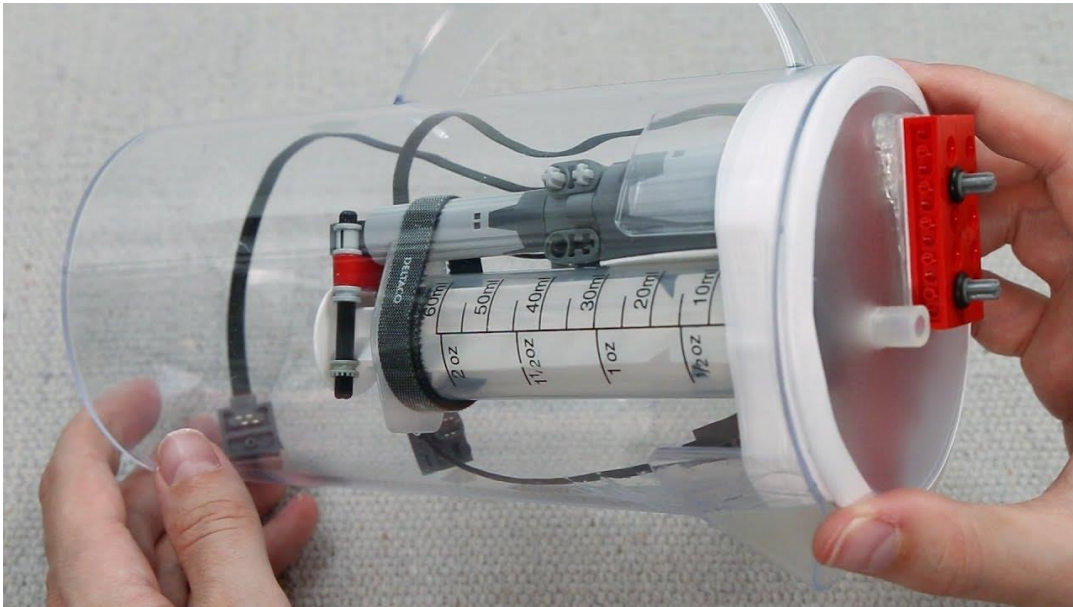


Figure 32: Syringe Ballast Example

Our design for the syringe ballast would be very similar to Figure 32. In the picture there is only one 60 mL syringe used and in the original video, the creator added metal as weight to make it neutrally buoyant. In our design we decided to have more syringes so that we are able to get more control and more water added into the system. We would also have a separate container that could be filled with water to ensure that it is neutrally buoyant.

3.10.3. Gas Ballast System

The design of a gas ballast system would include a container of low-pressure gas in a container in liquid form. This container would be put inside the ballast tank. Using a servo to open the tank would allow water to flow into the tank filling it and sinking the submarine. We would then be able to release some of the gas from the container which would force out water and allow the submarine to float back up to the surface.

The inherent problem that we saw with this design is the use of the gas tank. It is an extremely simple system only needing a valve to fill the tank and a container of liquid gas. The gas tank would only have a limited amount of uses however and would need to be changed after a certain amount of uses. This could leave us in a bad situation if we ever forget to change the container and has the possibility of leaving our submarine stranded below the water.

This method would be able to provide us a very fast and consistent method of lifting our submarine up from the water. It would also cause a lot of trouble because the more often we use the submarine, the more often we would have to replace or refill the gas canister. This would have us opening and closing the submarine, potentially risking a leakage due to user error, or the sealing parts getting degraded after repeated use opening and closing the submarine. This is why we felt that this method would lead to more trouble than it is worth.

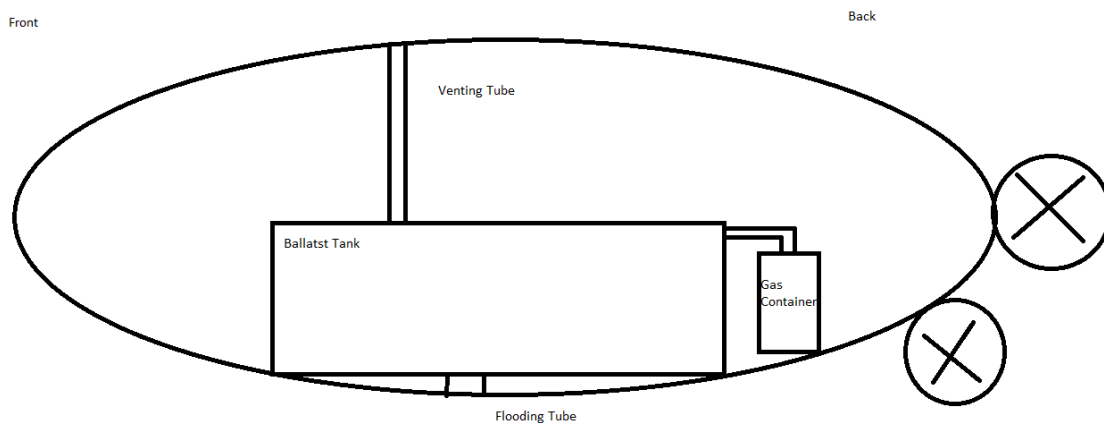


Figure 33: Gas Ballast Example (Created by the Authors)

Figure 33 shows how the gas ballast system would be laid out. There would be a single tank that would hold all the water we want to fill it with. When the venting tube is opened it would pull water in through the flooding tube and into the ballast tank. Then when we want to surface, we would shut the venting tube and open the tube to the gas container. Then as gas flows out of the container it would push the water back down through the flooding tube, clearing the ballast tank.

3.11. Water Pumps and tank

This design idea is that we would have a container that would have two water pumps attached to it. One pump would fill the container with water from outside the submarine decreasing its buoyancy and causing it to sink down, while another pump would be used to pump out the water and increasing its buoyancy. This method would allow for simpler assembly while still getting a good amount of ballast. It has the added benefit of taking up as little space as possible.

As seen in Figure 34 below, one pump would fill the ballast tank while the other would drain it. Pump one is in the best spot to fill the tank, while pump two would be used to drain it. An important thing to note is that the exfil pump, pump two, should be attached to the ballast tank at the lowest possible spot so that it can effectively drain the entire tank. The inflow tank on the other hand does not need to be placed anywhere specifically as it is just filling up the tank.

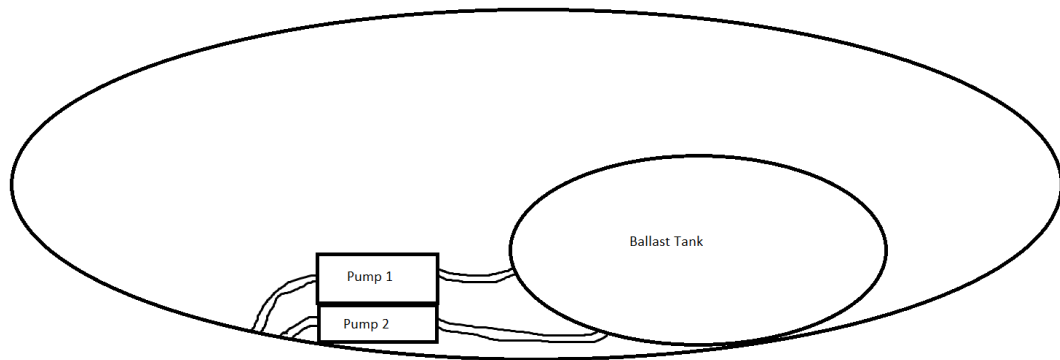


Figure 34: Water Pump Example (Created by the Authors)

3.11.1. HEEPDD Submersible Water Pump

The water pump in Figure 35 is about 2 inches by 1.5 inches by 1.5 inches which is good because it is small and will be easy to find a spot for it to fit in the submarine. It only needs 5 V and 170 mA giving 120 L/h worth of water which is certainly a lot for our ballast tank.



Figure 35: HEEPDD pump

3.11.2. Pulaco Submersible Water Pump

The Pulaco design in Figure 36 is quite small at 1.5 inches by 1.5 inches by 1.1 inches. This would be a good fit for our submarine because we want to save as much space as possible on the design. This also gives an output of about 190 liters per hour which is a lot of water to move. Overall, it is a good design, with one exception, it's built to work on a 120V 60Hz AC power source such as a wall mounted outlet.



Figure 36: Pulaco pump

3.11.3. Hygger Ultra Quiet Pump

The Hygger, Figure 37 is a bit large compared to the other pumps, coming in at 2.4 inches by 2 inches by 1.7 inches, but this one can output an even 200 liters per hour, even coming with an adjustable flow valve. Overall this pump seems a

bit too big for our design, and those problems are made worse by the fact that it is intended for a wall mounted outlet, needing 120 V 60hz AC Power.



Figure 37: Hygger pump

3.11.4. Winkeyes Submersible Fountain Pump

The Winkeyes pump, Figure 38, is a bit large at 1.61 inches by 1.34 inches by 2.16 inches. This pump would give us a huge output of 240 liters per hour, needing only 12V and 3.6 W of power.



Figure 38: Winkeyes pump

3.11.5. Pump Comparison Chart

In Table 13 below we compared a few of our different choices for water pumps. Overall, our main concern was power consumption, and voltage requirements which put the HEEPDD model as our best available option using only 5V DC, and needing less than 1 watt of power. Our good second option was the Winkeyes due too it being cheaper and relatively the same size, however it needed more power at 3.6 watts at 12V DC.

Table 13: Pump Comparison Chart

	HEEPDD	Pulaco	Hygger	Winkeyes
Voltage	5 V	120 V	120 V	12 V
Power	0.7 W	3 W	3 W	3.6 W
Liters Per Hour	120	190	200	240
Length (in)	2.17	1.5	2.4	1.61
Width (in)	1.61	1.5	2	1.34
Height (in)	1.34	1.1	1.7	2.16
Cost Per Unit	\$12.09	\$11.99	\$10.99	\$9.99
Inlet Diameter	8 mm	7.62 mm	7.9375 mm	7.874 mm

3.11.6. After Demo Ballast and Pumps Update

Our design was changed to include two types of pumps: a small inlet pump, and a large outlet pump. Despite a promising midterm demonstration performance, the small pump needed to be replaced due to not having the pressure to overcome the end pipe system. The small head value (pressure number) that the HEEPDD produces (reflected in its small liters per hour outflow number) meant that it wasn't strong enough to use in the end system. As such, it was replaced by the 12V Bayite BYT-7A015 Hot Water Heater Circulation Pump. While being double in price, its flow rate when converted to liters per hour is nearly four times the maximum flow rate (476.96 liters per hour) of the HEEPDD. Additionally, it has the downsides of requiring more power and is larger, however, with the time crunch to getting a working submarine, consideration of other parts so late into the process was sidelined in favor of its ability to work. The large pump chosen was the 12V Ironton Water Pump, selected for its greater head value and low head/weight ratio. Both pumps are shown below in Figure 39.



Figure 39: Large Pump and Small Pump (Created by the Authors)

As part of the water pump and tanks method of ballast, an appropriately sized bladder container needed to be acquired. Along with that, we wanted a bladder that could expand, and hold a large enough amount of water to change the neutral buoyancy of the submarine. So if more water was pumped in to the system as required to sink, the bladder needed to resist any internal forces trying to explode the bag. We chose to use the 2 liter SKL Hydration Bladder (Figure 40), as it was resistant to forces trying to crush it (so it would resist expanding inside the submarine body and resist being pierced), a one-way valve, and could tolerate liquids between -20 and 50 degrees Celsius as dictated by the secondary engineering specifications.

However, the large size made it difficult to fit all other internal components inside the submarine, and risk of puncture risked leaking water onto other parts of the submarine and damaging them. Additionally, this amount of water was discovered to initially be insufficient in changing the neutral buoyancy of the water due to a miscalculation in the overall submarine buoyancy. This was rectified by buying additional static ballast – 2 foot long #5 rebars that lay under the mounting plates for the parts, as opposed to changing the size of the bladder.



Figure 40: SKL Hydration Bladder (Created by the Authors)

3.12. Ultrasonic Sensor

This section is dedicated to deciding which pieces would be best to use for our ultrasonic sensors that would be in the back of the submarine to help prevent us from backing up into something. The chosen sensor must have a good distance and resolution and should ideally be cheap enough to allow for multiple of such sensors to be purchased. They should be waterproof, such that when they are exposed to a body of water they don't let water through themselves and flood the rest of the submarine. It should also have a quick response time such that we can get more frequent updates of what's behind the submarine.

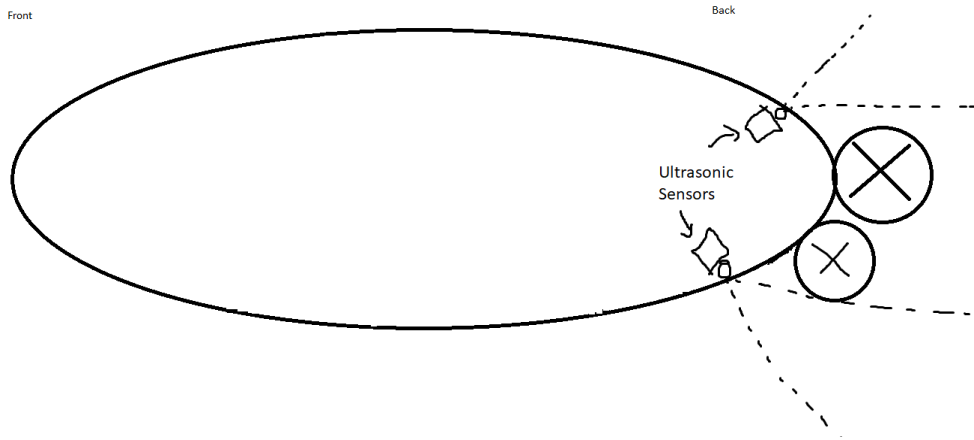


Figure 41: Ultrasonic Sensor Layout (Created by the Authors)

The information that we get from the ultrasonic sensor will be routed back to the controller held by the user. This will allow us to warn the user when they are approaching any sort of object and are in danger of backing up into it. Having this implemented will give us a reduced risk of crashing the submarine into something while still providing an easy-to-use system for whoever is controlling it.

Our essential design for the sensors is that we will have two of them on top and below the propellers. This way we will be able to get an accurate reading of what is behind us without the propellers getting in the way of the sensors or appearing on our readings. An example of the sensor placement is shown in Figure 41.

3.12.1. Basics of Ultrasonic Rangefinders

An ultrasonic rangefinder will have two parts, a transmitter, and a receiver. Sometimes these will be combined into one component called a transceiver. The transmitter will send an ultrasonic wave, and this wave can bounce off an object and get sent back to the receiver side of the device, as seen in Figure 42 below. For underwater use we need to ensure that it is an acoustic wave being sent out because that will allow the signal to reach further without degrading, allowing us a more accurate view on how far our submarine is from any given object.

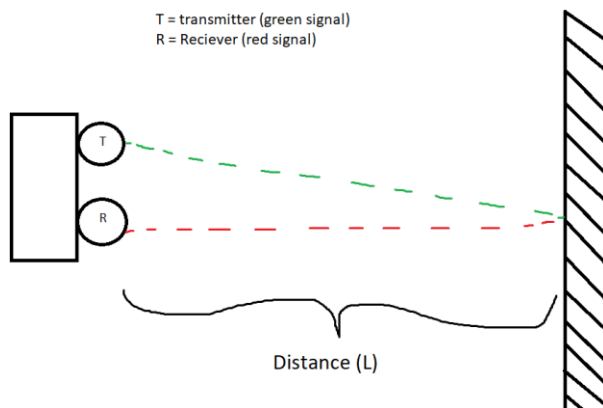


Figure 42: Ultrasonic Rangefinder Diagram (Created by the Authors)

According to Figure 42 above, the signal that gets sent out will travel some distance, L, and either reflect off an object and get sent back to the receiver or, if there is nothing in front of it, the signal will continue off into the distance not colliding with anything. If the object is reflected the receiver will give off a voltage, and if no signal is received it will not give a voltage reading. We can use the time between the signal being sent from the transmitter, and the signal being received by the receiver to determine the distance between the sensor and an object, if there is any object at all, using the formula below.

$$L = (1/2) * T * C$$

L = Distance

T = Time between
emission and reception

C = Speed of Sound

Figure 43: Distance Formula

When using the formula in Figure 43, we have to remember that there is a difference between the speed of sound above, and below water. This change in speed is due to the increase in density and decrease in temperature that we would experience underwater; this would make the sound significantly faster than it would normally be above water. At sea level and 20 degrees Celsius sound travels at a speed of 343 meters per second, but under freshwater at 20 degrees Celsius it travels at 1481 meters per second due to the increase in particle density around it. Making this mistake could cause over 200% error in our calculations. Fortunately, once underwater the speed of sound does not change very much until you drop a couple kilometers or experience a large temperature change. This is because the speed of sound increases by 17 meters per second per kilometer of depth, and 4 meters per second per degree of Celsius.

3.12.2. HiLetGo TCT40

The TCT40 sensor pack, in Figure 44, that we found was a package of ten transmitters and ten receivers. This would be very useful for us because we could easily install these separate pieces in the exact locations that we desire them. The one complication, however, is that they are not waterproofed by

design. We would have to add on some sort of waterproofing to these components since they are intended to be submerged for their entire function.

This component's nominal frequency is 40 kHz and emits a sound pressure greater than 110 dB, while the receiver is sensitive to -75 dB at minimum. Each piece is marked as either "T" for transceiver or "R" for receiver, making assembly very easy.



Figure 44: HiLetGo TCT40 sensor

3.12.3. HiLetGo Ultrasonic Sensor Transceiver

This ultrasonic sensor in Figure 45 comes already constructed to be waterproof and would certainly be an easier piece to install and use. Its nominal frequency is about 40 kHz and has a detectable range of 0.3 meters to 3.5 meters. Although we would only need about one meter of warning for backing up our submarine, it would be useful to still have that longer range for safety's sake.

This product is very simply designed and could be easy to fit into a variety of applications. However, the simplicity is actually a downside for us in this product, because we would prefer to have something made with underwater use in mind.



Figure 45: HiLetGo Ultrasonic Transceiver

3.12.4. SEN0208

The SEN0208 made by DFRobot in Figure 46 is a different type of underwater sensor that comes with a cable to be easily plugged into a Arduino board. Its operating voltage is 5 volts, and has a range of 25 cm to 4.5 m.

We are not using an Arduino board for this submarine, which is a large downside of this product. It is however already waterproofed and has a cable so that we can place the sensor away from the actual circuit board which are two strong positives for this product. After a lot of deliberation, we decided that this product would be best for our submarine due to its large range capabilities and also its design as a waterproof sensor.



Figure 46: SEN0208 sensor

3.12.5. SainSmart HC-SR04

The SainSmart HC-SR04 in Figure 47 is a great looking product for this project because it has a very large distance range, from 0.02 m to 5 m, and is also designed for a board's use having an operating voltage of 5 V. One problem it does have though is that it is not waterproofed by design so that would make it harder to integrate into our submarine's design because we would have to waterproof it ourselves.

Though this product has the best available range and is not drastically more expensive due to this, it was not quite the best product available due to it not being waterproof, and also the fact that it was designed for use with an Arduino instead of a Raspberry Pi. This device was a very close second in our decision-making process thanks to its impressive range.



Figure 47: SainSmart HC-SR04 ultrasonic transceiver

3.12.6. 400SR160

The 400SR160 in Figure 48 seems like a very standard product, like other sensors we've found. It's got an operating voltage of 10 V and is not waterproofed by design. Its effective range is a much smaller interval of value, ranging from 0.5 meters to 3 meters.

This could be useful if we wanted to have less range for the sake of not needing to filter out information that is too far away to be relevant. Though this could be a decent advantage, we decided that it would be better to have a larger range to work with so that we could customize precisely how far we want an object to be before it alerts the user that they are in danger of backing up into something. Overall it was not a very impressive product for our specified needs, but was close enough to what we wanted to be considered as an option.



Figure 48: 400SR160

3.12.7. Ultrasonic Sensors Comparison table

Table 14: Ultrasonic Sensors Comparison Table

	Range (Max)	Range (Min)	Operating Voltage	Waterproof
TCT 40	3m	0.5m	10 V	No
HiLetGo Transceiver	3.5m	0.3m	10 V	Yes
Sen0208	4.5m	0.25m	5 V	Yes
SainSmart HCSR04	5m	0.02m	5 V	No
400SR160	3m	0.5m	10 V	No

Table 14 above shows that we will proceed with the SEN0208 because of its range and waterproofing.

3.13. Power Analysis

The power distribution analysis in Figure 49 below shows how the power will flow through our design. Power will originate with the 60 V Greenworks battery. This will go to the Controller PCB, which will power the land Raspberry Pi via USB-C cable. The power will then go from the Controller PCB through the Ethernet cable to the Drone PCB.

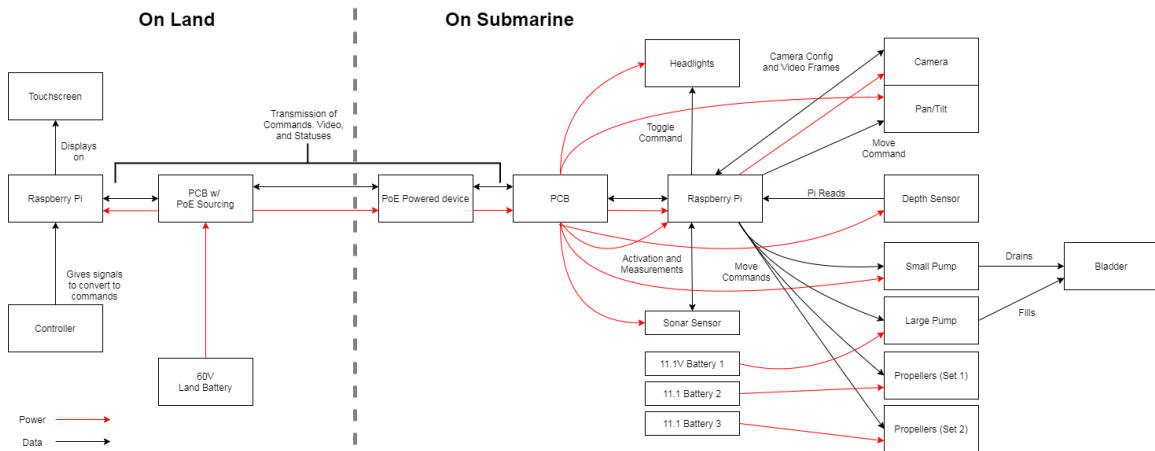


Figure 49: Power Distribution (Created by the Authors)

This PCB is described in another section. The power will flow from the Drone PCB to the headlights, the Raspberry Pi and its video camera attachment, sonar sensor and the small water pump. Each set of propellers (right, left) will each have their own battery, as they take up way too much current to use the Ethernet cable for. Also, the large pump will also have its own battery.

3.14. Basics of Ethernet

Ethernet was designed in the 1980s and connects all of the devices in a household to the same LAN (Local Area Network) so that they can create, store, and share information with others in the location. A router is typically used to be the “hub” of all these devices, so all the devices connect to it via Ethernet cables.

When it was first invented and first being used, it relied primarily on coaxial cable, but has now morphed into being mainly twisted pair copper wire or fiber optic cabling. Data is transmitted through these Ethernet cables, so there must be 4 pairs of wires, consisting of two pairs for voltage, and two pairs for communication signals. The pairs of communication signals include the transmit signal strand and the receive signal strand. They are twisted, because the communication signals would get interrupted otherwise and the data would not end up in the correct places to be received. One of the more important aspects of twisted pair is its signal noise reduction properties.

There are different speed variants of Ethernet cable, including CAT 5, 5e, 6, 6a, and 7. Cat 5 and 5e can transmit and receive speeds of up to 100MB/sec, Cat 6 can transmit and receive data at up to 1 GB/sec, and Cat 6a and 7 can transmit and receive data up to 10 GB/sec.

Ethernet can either be transmitted using half duplex mode or full duplex mode. Half duplex mode is where data is only sent or received in one direction at a time, whereas full duplex can transmit and receive data at the same time.

When Ethernet is being used on fiber-optic cables, the data is transmitted very fast. Glass and plastic are used to transmit the data technically at the speed of light, but as it has a medium to go through instead of a vacuum, it will travel 31% slower than in a vacuum.

Gateways and bridges are used to connect multiple Ethernet networks together to communicate. Gateways connect two different systems together, and a bridge connects two similar networks together.

Looking a little deeper, Ethernet connects paths using two variants: The Logical Link Control (LLC) and the Media Access Control (MAC). The LLC establishes paths on the Ethernet to transmit data between devices, whereas the MAC uses the specific code identified in the connector to identify data transmissions.

Data is sent using the standard of Carrier Sense Multiple Access with Data Collisions (CSMA/CD) to avoid the data packets being interrupted or a broken packet being transmitted. This means that the data is sent little by little to check for collisions. If there is a collision, a flag is raised and then a waiting time occurs before it transmits another piece of the packet.

3.14.1. RJ45 connections

An RJ-45 (sometimes called an 8P8C) connector is a common Ethernet cable terminator, and comes with a stress relief tab and with eight wires inside of it. As shown in Figure 50 below, there are green, blue, orange, and brown pairs of wires. The blue and brown wires carry the voltage through, and the orange and green pairs of wires carry the communication signals. This way, there is such a thing as Power over Ethernet (POE).

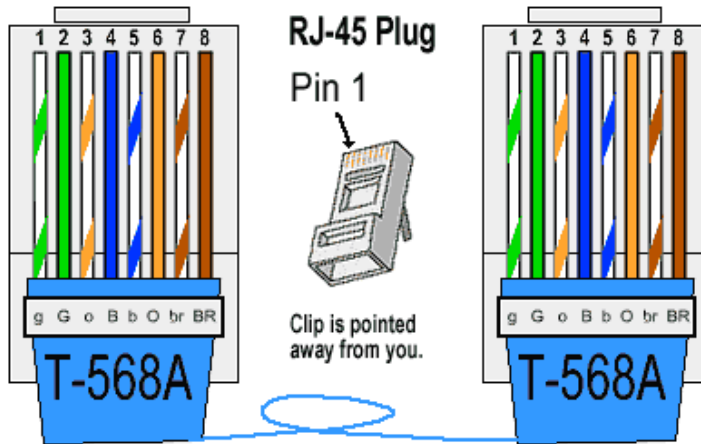


Figure 50: RJ45 Configuration

3.14.2. Power over Ethernet

The tether cable from the PCB and battery on land that attaches to the submarine will need to be at least a fifty foot long Ethernet cable. It needs to be at least this long because our specs say that the submarine will be able to go to a depth of 15 m and there needs to be some leeway.

Power over Ethernet allows one RJ45 cable to provide both data connection and electric power to powered devices, by splitting the wires in the cable between power and data, instead of having separate cables. Figure 51 below shows the flow of power by way of an example of PoE. The power comes in from one source, which will go to a PoE switch, which will then go to all the other powered devices on board the submarine.

In our case, the power will be delivered from a battery on land, which will be attached to the printed circuit board with Ethernet connection and the hand-held controller. The on-board Raspberry Pi will tie into that PCB, via an RJ45 Ethernet cable where the communication signals and the electrical power can be transmitted to the submarine. Then from that PCB, the power will go to the Raspberry Pi onboard the submarine along with the communication signals, to the other PCB with the PoE switch.

Table 15: Power over Ethernet types

Property	802.3af (POE)	802.3at (POE+)	802.3bt Type 3 (POE++)	802.3bt Type 4 (POE++)
PD* available power	12.95 W	25.50 W	51 W	71 W
Max delivered PSE** power	15.40 W	30.0 W	60 W	100 W
PD voltage range	37-57V	42.5-57V	42.5-57V	41.1-57V
PSE voltage range	44-57V	50-57V	50-57V	52-57V
Max current	350 mA	600 mA	600 mA per pair	960 mA per pair
Max cable resistance per pairset	20 Ω	12.5 Ω	12.5 Ω	12.5 Ω
Power management class levels	3	4	6	8
Temperature Rating Degradation ($^{\circ}$ C)	N/A	5 with two active pairs	10 with more than half of pairs at max current	10 with temperature planning required
Minimum Supported Cable	Cat. 3	Cat. 5	Cat. 5	Cat. 5

*PD stands for PoE Powered-Device

**PSE stands for PoE Power Sourcing Equipment

A device can only send or receive if it has the matching port type (PD or PSE).

As seen in Table 15 above, there are different types of Power over Ethernet. Our original plan was to use 802.3at, which is PoE+, where 25.5 W can be transmitted. This value is derived from the 30 W, which is the maximum power that can be delivered, and then calculated at 85% capacity. However, according to our power analysis, we need more power to flow through this cable. To

accomplish this, we decided to investigate further 802.3bt, which would provide us with 51 W of useable power when connected similarly to Figure 51 below.

The biggest benefit of using Power over Ethernet is that it will allow us to create a submarine that is both smaller and lighter. Having a reduced size will mean we need less ballast to keep the submarine lowered and having it lighter will make it more convenient for the end user to store and take with them. This does mean that they will also have to take the battery with them, but we think that is balanced out by the increased convenience of recharging the battery.

Without Power over Ethernet the battery would have to be inside the submarine meaning that whenever it needs to be charged the user would have to open the submarine. This can lead to many problems, most worryingly that the user could improperly close the submarine after charging it or that the parts keeping the submarine air-tight would degrade over repeated use. If either of these would happen then we would have a huge potential for water leaking into the submarine while it's in use which would be catastrophic.

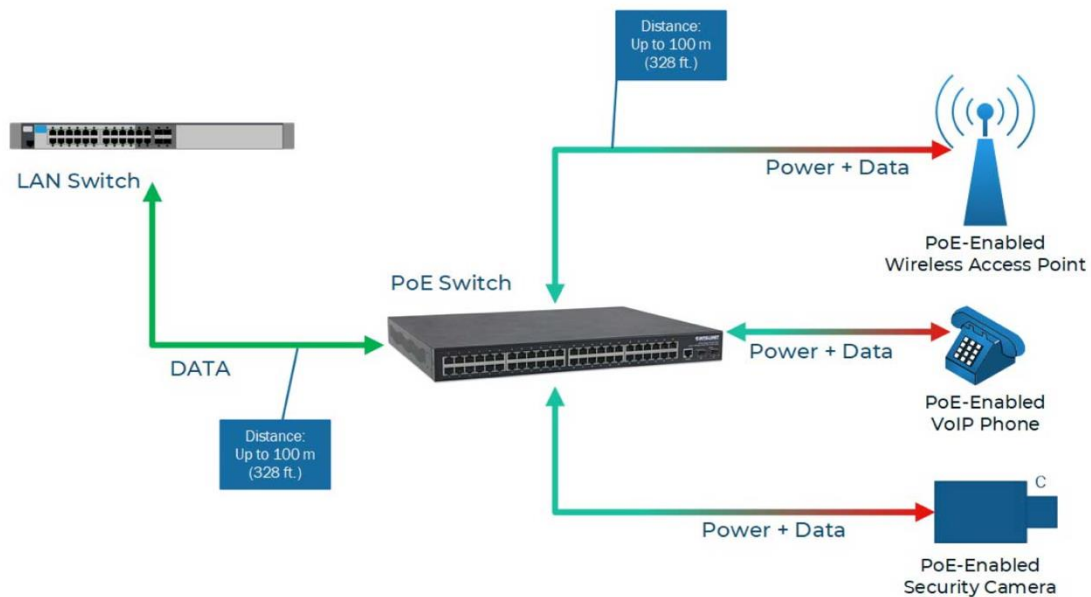


Figure 51: Ethernet Block Diagram

3.15. Waterproofing the submarine housing

A huge part of building our submarine has been our thoughts about how we are going to keep the submarine waterproof because a water leak while it's being used would lead to a total failure of our device. To avoid having water spill all

over our electronic pieces we selected a few parts to help keep the submarine waterproofed.

To waterproof the housing, we have several methods. We plan on putting Marine Weld [40] around the case for the Go-Pro, which will both hold the housing together around it as well as keep water out. The Marine Weld as seen in Figure 52 below is a great resource that has been tested and is very reliable. This epoxy can be used on aluminum, fiberglass, metal, plastic/composite, wood, carpet, deck hardware, gallery parts, engine parts, trailers, housing and blocks, shafts and pulleys, fasteners, and rivets. As such this satisfied our requirements.



Figure 52: Marine Weld

As an alternative adhesive to the marine weld discussed above, we could use clear Room Temperature Vulcanizing (RTV) rubber, which is commonly available from Home Depot and other home improvement stores. It is commonly used to seal window edges and the like. It forms a pliable bond that can be easily reworked with a knife or other sharp implement, whereas the marine weld forms an effectively permanent concrete-like substance that is difficult to rework. The marine weld would require a solvent to dissolve that might damage the submarine or its components. An example of RTV is shown in Figure 53 [53].



Figure 53: JB Weld RTV

Another way we will waterproof the submarine housing is by using specialized grommets. We need to get the Ethernet cable into the housing somehow, and this needs to be flexible to accommodate it coming in any direction. That is why we have picked out some grommets similar to the one pictured in Figure 54 below. They come in sizes allowing a range of cable diameters from 0.12 inches to 0.51 inches. This will allow us to have all our wires coming safely in and out of the submarine while maintaining airtight integrity.



Figure 54: Waterproof Grommet

The grommet pictured in Figure 54 may be purchased from Amazon in packs of various quantities, allowing us to have extras should we require them. This grommet will allow the cable to pass through an opening in the submarine hull and provide a leak-proof seal. The grommet comes in two parts as can be seen above. The main part passes through a hole in the hull, and then the nut comes in on the other side and is tightened. An O-ring built into it provides the seal. This will ensure no water comes inside of the housing that could potentially ruin any of our materials and wiring on the inside, leading to an overall catastrophic failure of our submarine. All the wires that attach to the propellers will also come through one of these grommets. This is essential because being able to manage our cables well, and also ensure the integrity of the submarine will be essential to its function. The convenience of these grommets, as well as the price was a very nice find from Amazon.

4. Printed Circuit Boards (PCBs)

We made two separate PCBs for this project. One PCB was on land and acted as a PoE switch. The other was located inside the submarine, and this one acted as a PoE Powered Device. These voltage regulators in the Powered Device allowed the voltage to be regulated down to 5 V, so each component attached to this board would only get 5 V.

The electrical schematic designer software called Altium will be used to create and print the PCBs.

To integrate the 802.3bt Ethernet into the circuit board, we have decided that we need to use a LTC 4291-1 from Analog Devices. This is a 4-port IEEE 802.3bt PoE power sourcing equipment (PSE) Controller. Its chipset is able to greatly dissipate heat on a per channel basis. It includes advanced power management features such as 14-bit current monitoring and is typically applied in circuit configurations such as Figure 55 below.

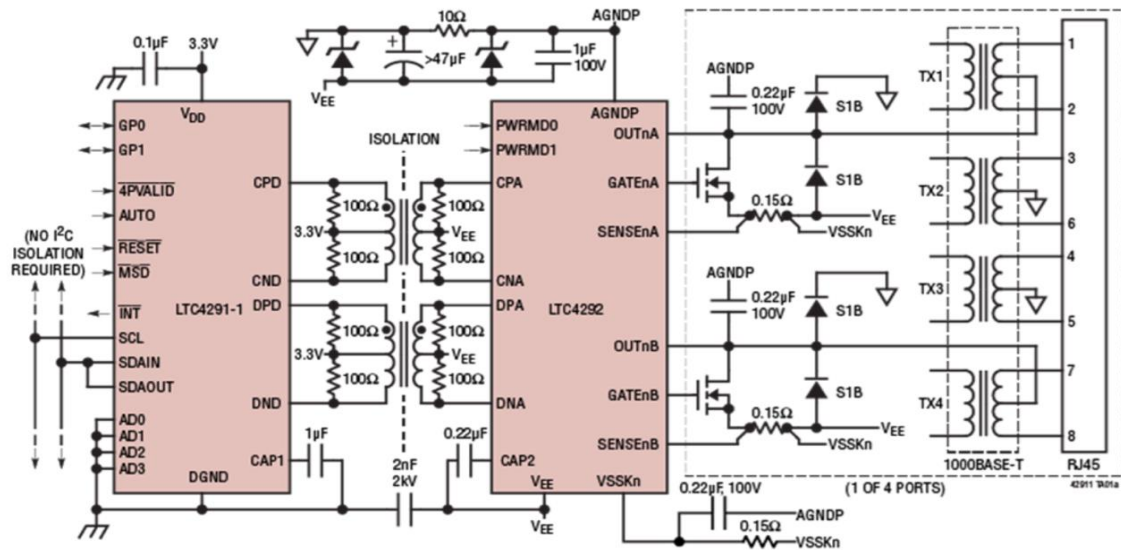


Figure 55: Example schematic incorporating an LTC4291-1

4.1.1. Schematic for Drone Board (After Demo Update)

We initially showed images of the PCBs focused on each section individually to improve readability. Among the content were various items, such as where terminal blocks were used, where batteries would connect, and denoting which components were the PoE Receiver and PoE controller. It also showed two voltage regulators (often misinterpreted as being the same due to their similar appearance) that regulated to 3.3 volts and 5 volts respectively. The PCBs were simulated using Multisim. This content has been replaced in favor of showing these circuits in context. See Figure 56 and Figure 57.

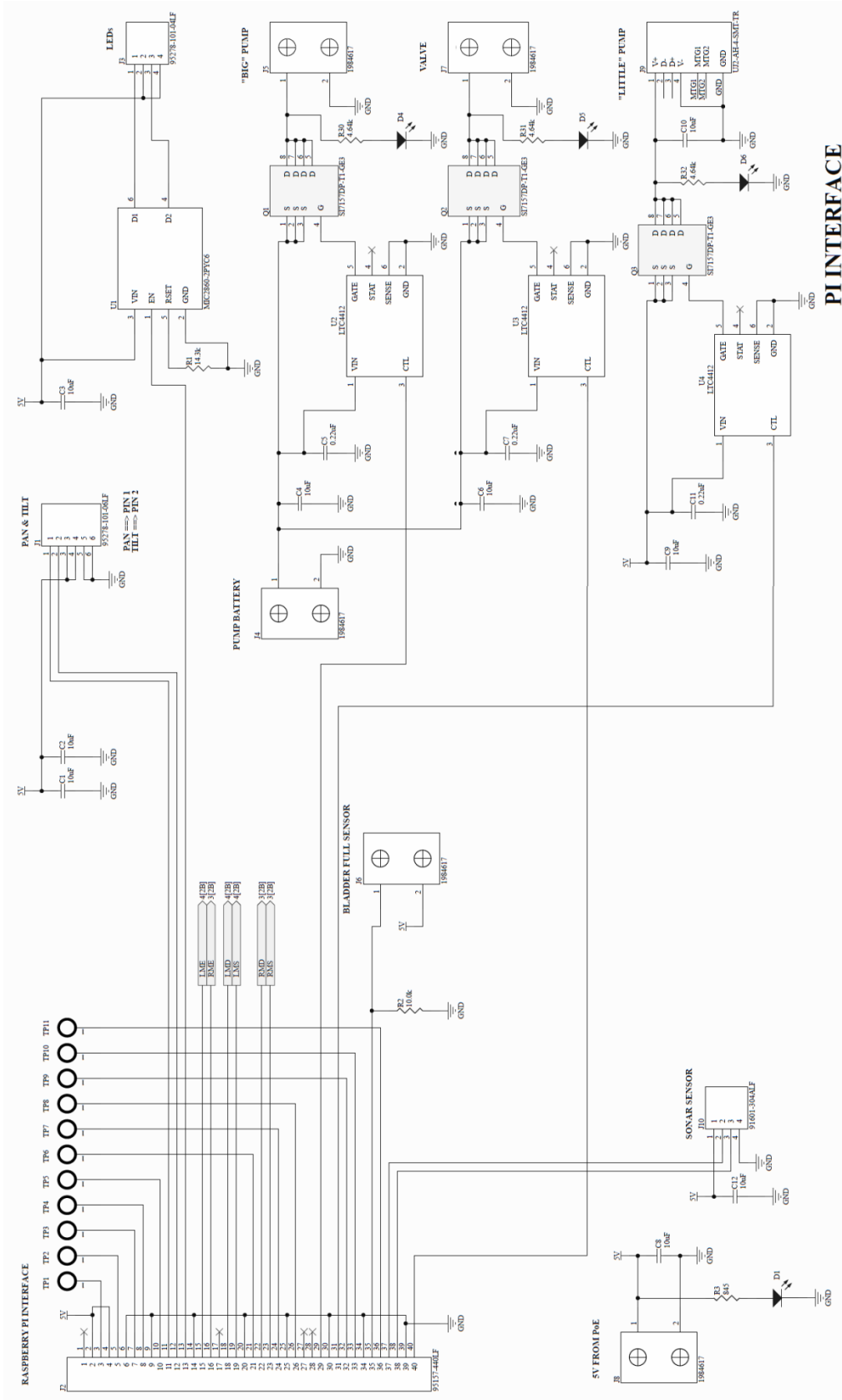
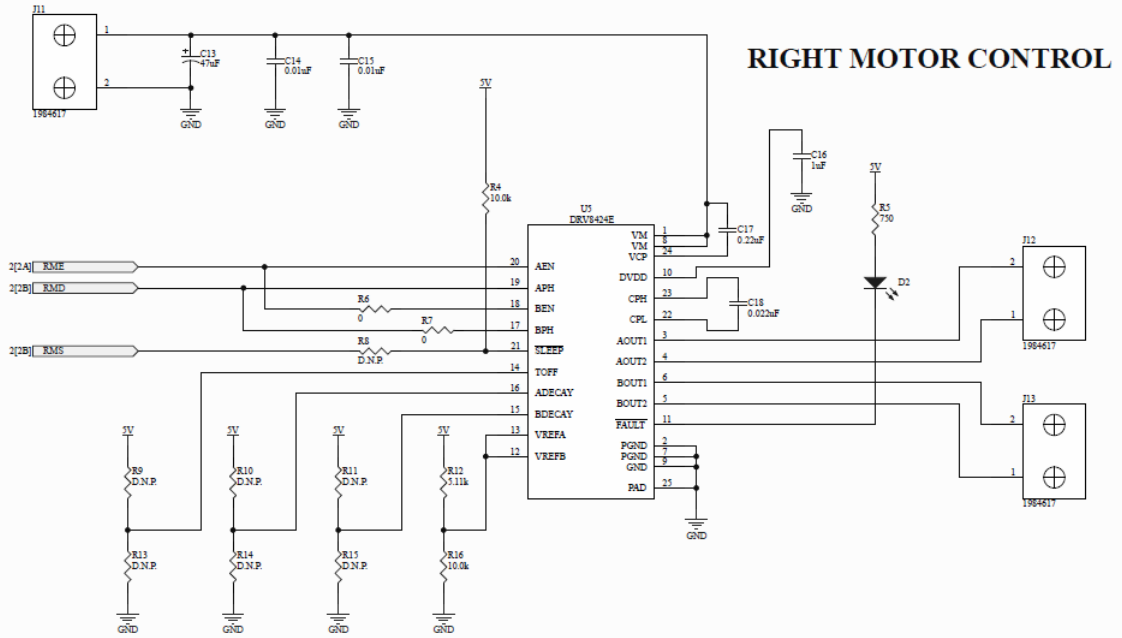


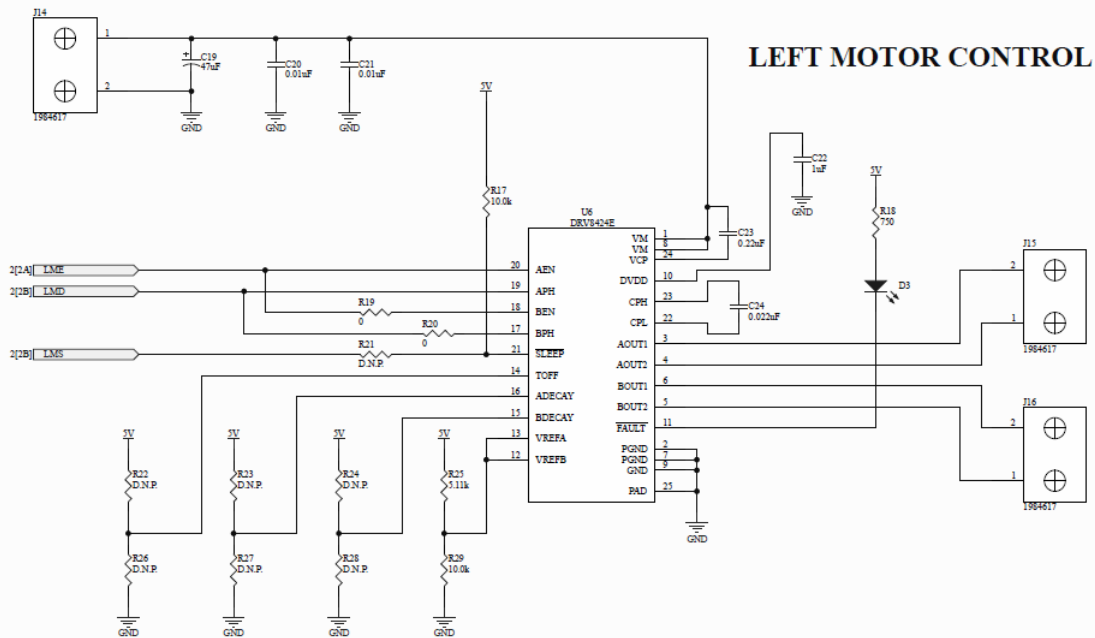
Figure 56: Pi Interface (Created by the Authors)

RIGHT MOTOR BATTERY



RIGHT MOTOR CONTROL

LEFT MOTOR BATTERY



LEFT MOTOR CONTROL

Figure 57: Motor Control circuits (Created by the Authors)



Figure 58: 1984617 Terminal Block

These terminal blocks, as seen above in Figure 58, will connect the outside components to the PCB. For example, the power source will come into the board through one of these, and wherever the power needs to go out, it will also go back out to one of these, except for the sonar sensors. The sonar sensors are the only piece that is a surface mount component. The other parts, such as the headlamp and the Raspberry Pis will need to be connected via wires, which will be grounded, and power supplied through these.

The light will be controlled via Pulse Width Modulation, so only power will need to go there with the rest of the terminal blocks that supply power to the other peripheral components. We still need to do some more testing with this, but this extra testing will occur after the PCB has been printed, and we can attach our components to the terminal blocks and watch signals pass through the Pi. Also, testing our code with this will prove that the correct connections have been made.

4.1.2. Schematic for Controller PCB (After Demo Update)

This schematic is much more complicated than the main board submarine. The data will come in via the Ethernet cable. The data and power will then travel from the PCB to the Raspberry Pi inside the submarine. Through this connection data will be both received and transmitted. Then power will go to the rest of the components and the data will be transmitted back through the PCB to the Raspberry Pi.

This set of schematics is composed of Figure 59, Figure 60, and Figure 61. Physically, this board sits in close proximity to the controller Raspberry Pi, and in the original design was intended to be paired as part of the custom controller. As that did not happen (see later sections) it was given its own box.

NOTE: BATTERY VOLTAGE INPUT IS A NEGATIVE VOLTAGE

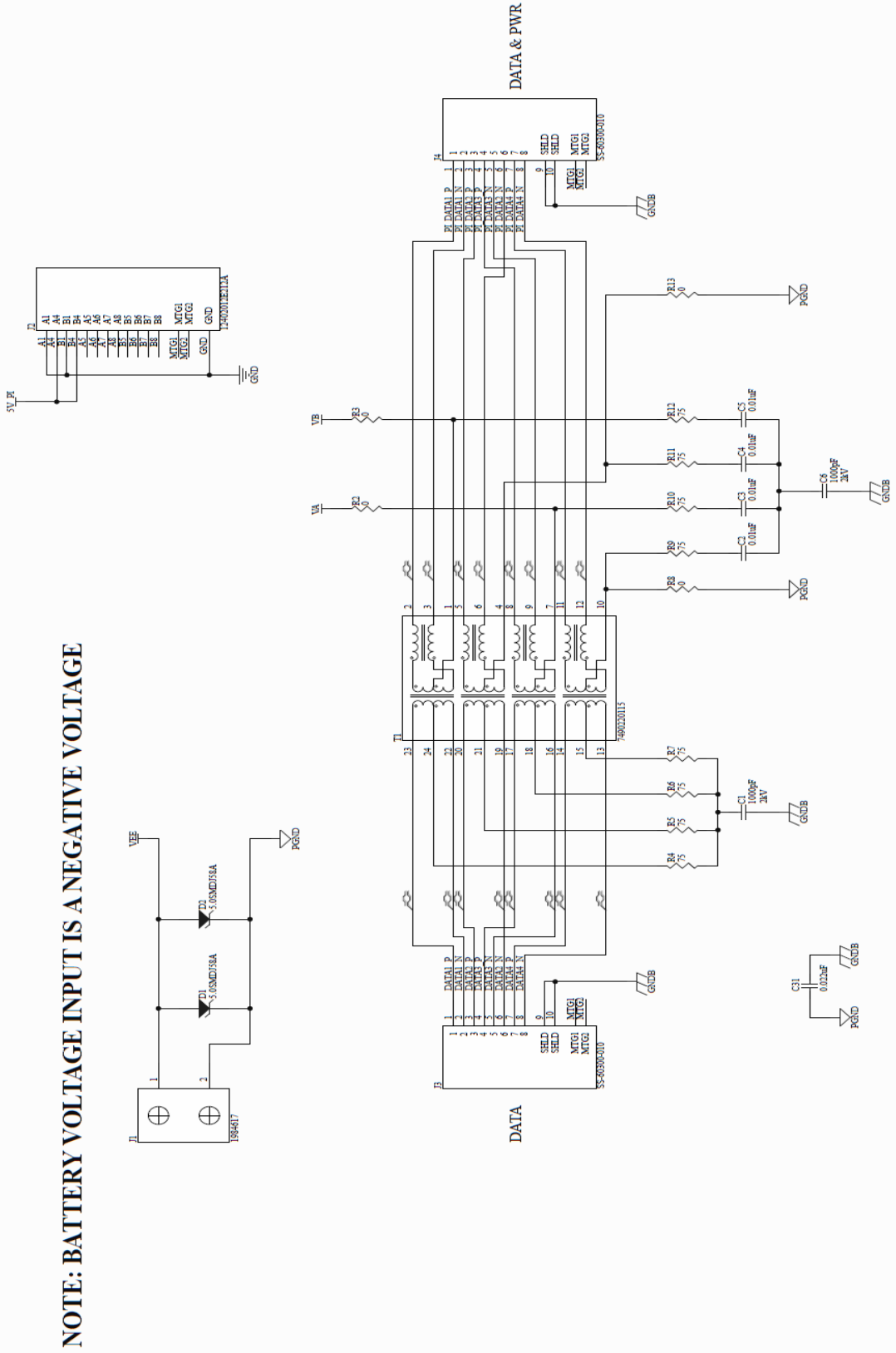
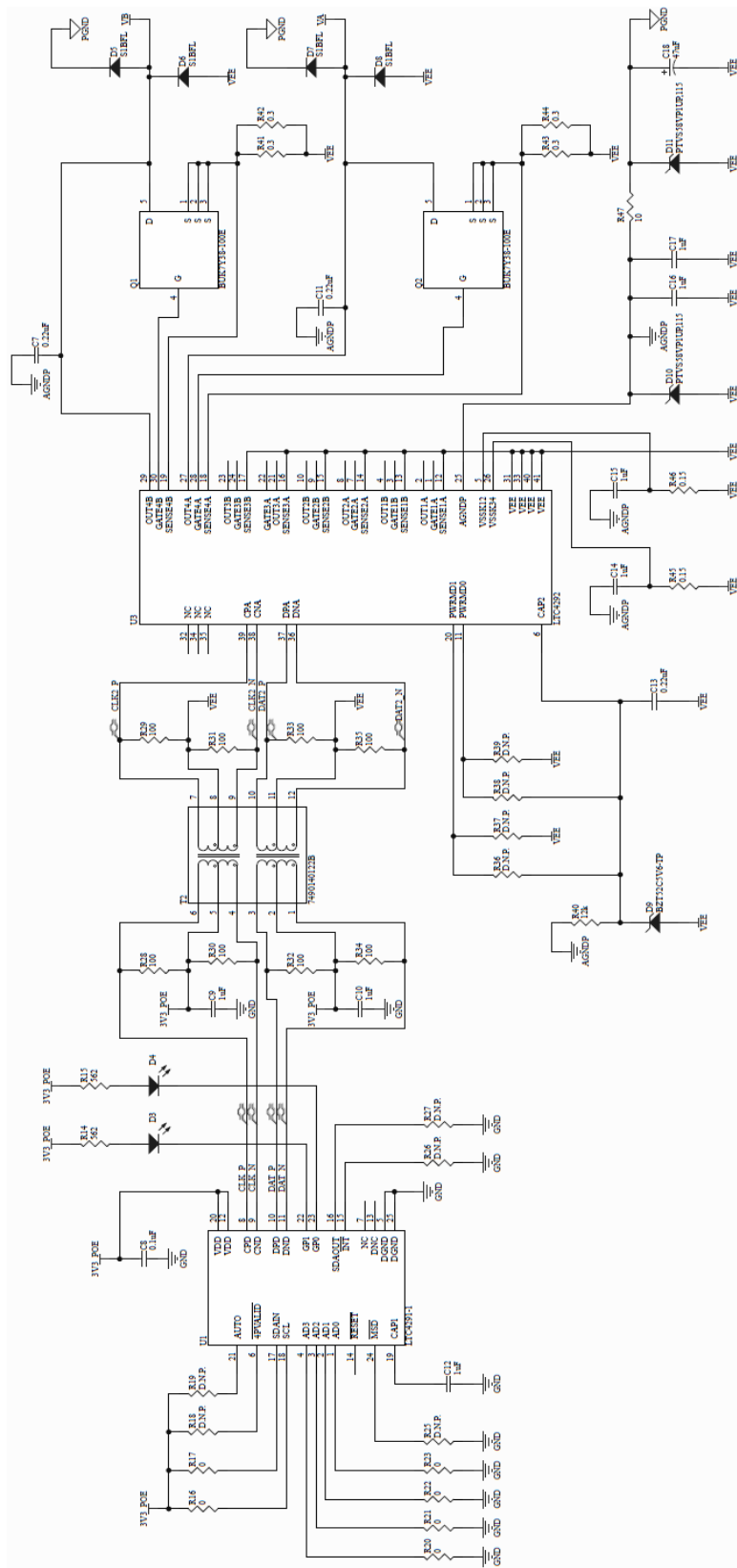


Figure 59: PoE Inputs (Created by the Authors)



PoE CONTROLLER

Figure 60: PoE Controller (Created by the Authors)

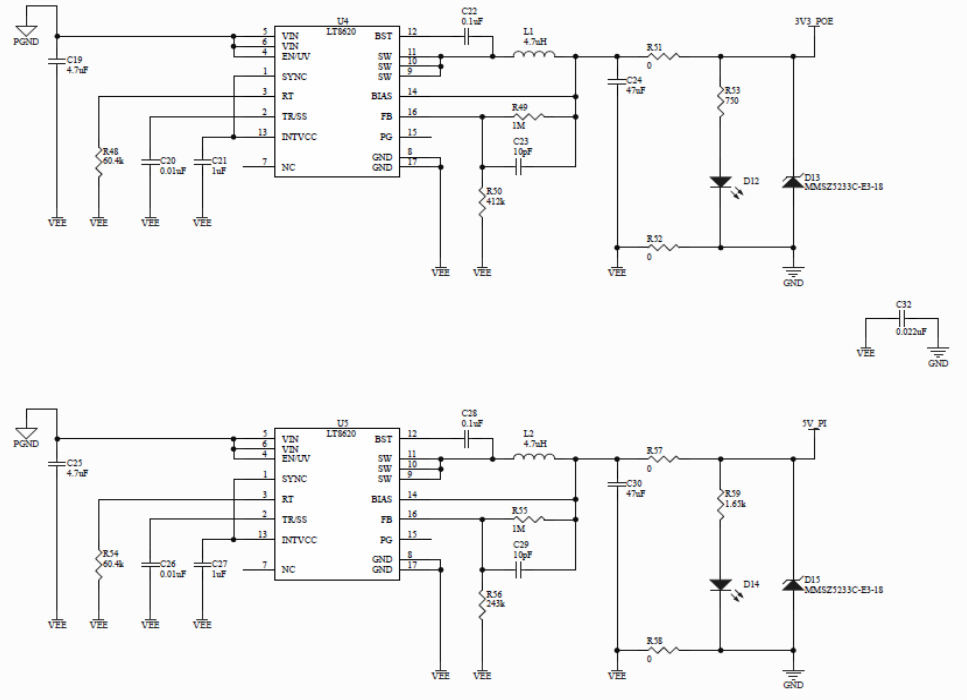


Figure 61: 3.3V Regulator (Top) and 5V Regulator (Bottom) (Created by the Authors)

4.1.3. After Demo Finished PCBs Update

The finished PCBs are pictured below in Figure 62 and Figure 63.

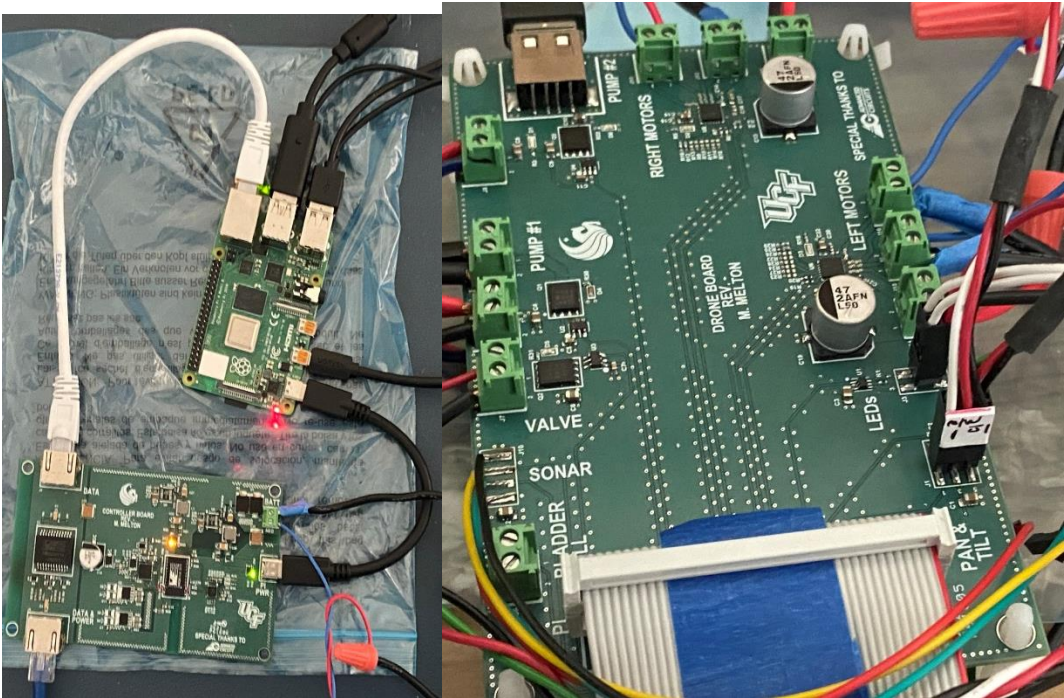


Figure 62: Controller PCB (Bottom) with Controller Pi (Top)

Figure 63: Submarine PCB on top of PoE Receiver (Created by the Authors)

5. Part Selection

The final parts chosen to be used on board the submarine are key to the success of the project. If parts are too large, or don't work as expected from our research, then the project could be delayed significantly. The following chapter details the parts to be chosen as well as the reasons behind choosing them.

5.1. Pump ballast

After some deliberation and testing we chose to use the pump ballast system as discussed in part research. This decision was made because of how simple it would be to integrate into the design.

We were deciding between the syringe ballast and this design and had a few reasons for this design being the final decision. With the syringes we would have needed a lot more free space to fit the design because of the syringes unchangeable shape, and the extra length needed to pull the plungers out fully. This design greatly lowers the space needed because the pumps do all the work, and do not need any expansion room. This also allows us greater control over how much water we want to be able to take in, since we will be designing the ballast tank.

This design is also a lot easier to integrate and bring into our full design because it requires less overall design work than the syringes. With the syringes we would have to design a system to push and pull the syringes in synch, whereas with this design we only must design space for it on the PCB and need no other design since it is a simple pump.

5.1.1. Pumps



Figure 64: HEEPDD Pump

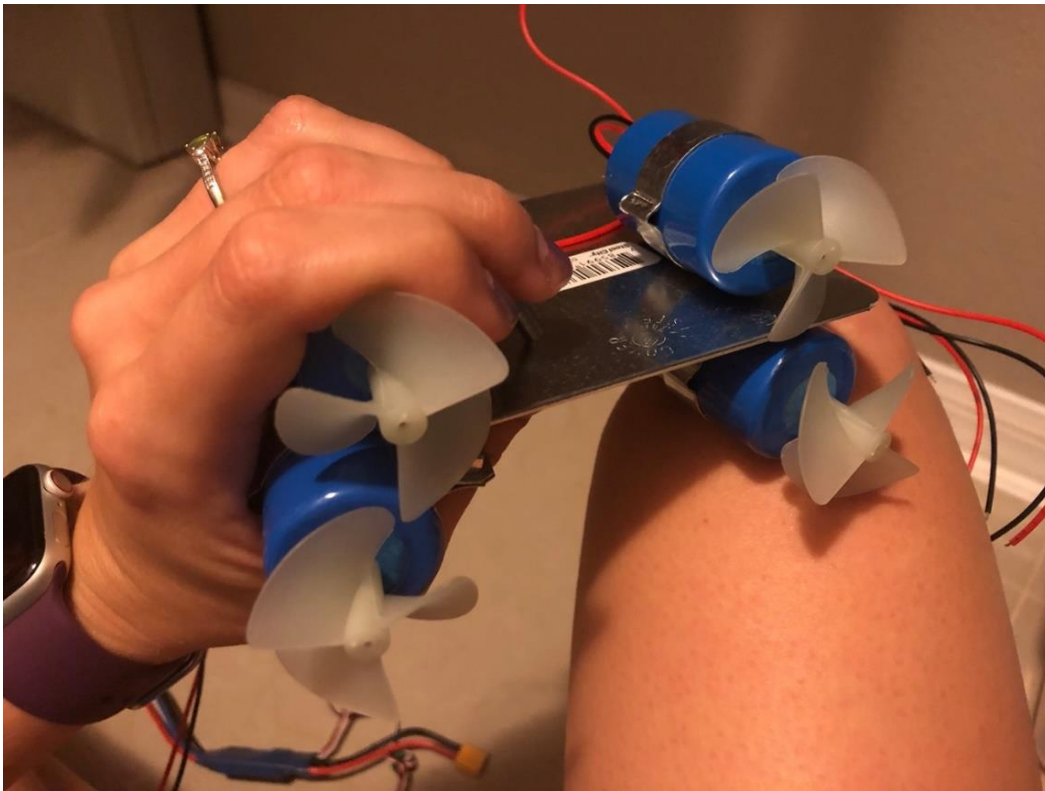
We decided to use the 5 V submersible water pump in Figure 64, because it is similar to those used for fish tanks in the home. This decision was made because it would be a smaller device. It would also be a lot simpler to integrate into our designs because its power requirements were so low. However, concern exists about its ability to pump when at depth, as the pressure from the pump may be too small to overcome the difference between the submarine and the ocean.

5.2. Propellers

The LICHIFIT RC Jet Submarine Underwater Motors from Amazon. As seen in Figure 65 below, they come in a 2-pack with one that spins clockwise, and the other that spins counterclockwise allowing for the best steering capability. These motors have brushes though, which we found out would be a lot harder to reduce the voltage coming to them.

We purchased two sets of these propellers so that we can have one on top, two on the sides, and one on the bottom. This way, it is easier to direct the submarine port, starboard, north, and south. When the voltage is cut off from all but the bottom propeller, the submarine will be steered north, and so forth. The way they are positioned is seen in the figure below. Obviously, the motors have not been secured to the plate in this picture.

Figure 65: Propellers (Created by the Authors)



5.3. Submarine Headlight

The flashlight seen in Figure 66 was chosen because it meets our requirement for being waterproof and able to operate at the depth that our submarine is being designed to operate at. More specifically, it addresses the low-light conditions in the underwater environment and enables us to traverse in potentially darkened areas such as under piers and underwater caves. By keeping the entire bulb housing, it's protected against the pressure and we won't have to be concerned about the bulb breaking or any electrical shorts. We deconstructed it, as seen below, so that it will fit into our housing and be able to be controlled by the PCB with a pulse width modulated general purpose input and output signal to control the brightness.



Figure 66: Deconstructed headlamp (Created by the Authors)

5.4. Cable

Our requirements for communication to the submarine are CAT6 or higher Ethernet cables. This type of cable includes four twisted pair wires in a plastic jacket and pre-terminated with RJ45 connectors on both ends. Using Power over Ethernet will allow us to transmit some power to supplement the on-board batteries. Our requirement is to have 50 feet of this cable, because anything greater than this distance will become unwieldy to test with none of us being diver trained. Model number BE-PEC6ST50 will be investigated during Senior Design II.

5.4.1. After Demo Cable Update

Despite the CAT6 being the preferred cable grade for PoE and high transmission speeds, it was determined to be unnecessary. A category 5 cable was used instead as it was able to provide the electrical and data speed needed. Although the rate was limited to 100 MBps, as opposed to the 1000 MBps previously discussed, 100 was sufficient as the framerate and control latency was well within acceptable amounts.

5.5. Cable Sheathing

The nylon sheathing as seen in Figure 17 was chosen because it meets our requirement for a light-weight, low-cost sheathing that will provide adequate protection from sharp rocks and possible fish teeth. This protection comes from the sheathing's great durability, as it is typically used in automotive and aerospace applications. As the Ethernet wire described in the above Section 5.4 will be fed through the sheathing, a 50 foot long sheathing will also be required.

5.6. Ultrasonic Sensor

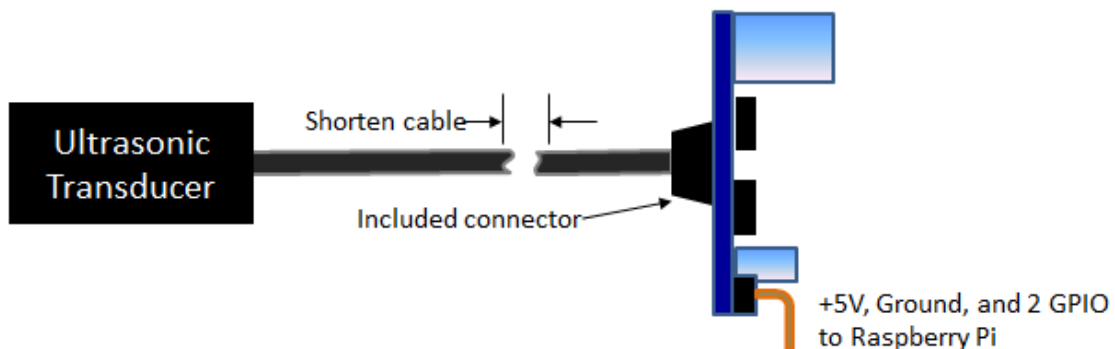


Figure 67: Connection between Ultrasonic Sensor and On-board Raspberry Pi (Created by the Authors)

We chose to use the SEN0208 made by DFRobot, because it includes a pre-terminated cable and it is easily interfaced to the on-board Raspberry Pi with four lines: a 5 volts line, a ground line, and two general purpose input and output lines. However, the 2.5 meters of cable length is not required inside of the submarine, so to minimize bulk it will be necessary to cut the excess length from the center of the cable and solder the wires back together to achieve an optimal length. See Figure 67 above.

Its simple design and low voltage requirement make it a very good choice for our submarine. It also has a maximum operating range of 4.5 meters which is more than enough for its intended purpose as our backup sensor.

A rear-facing sensor was added in lieu of a back-up camera to allow the operator to gauge distances of objects that they cannot see when reversing the submarine. This is important because objects they could hit include wildlife or sharp rock formations that could compromise the integrity of the submarine's hull.

5.7. Controller Original Design

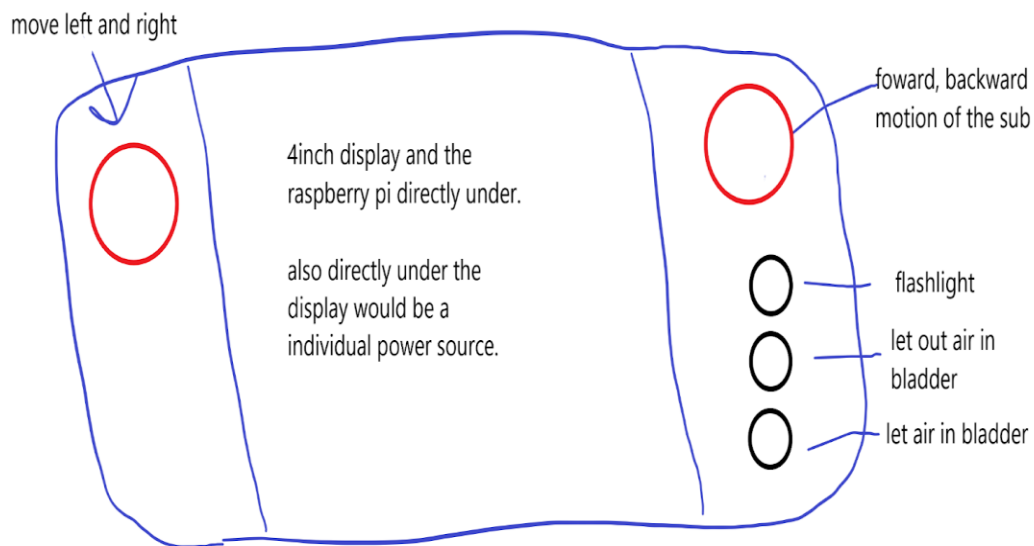


Figure 68: Original Controller Design (Created by the Authors)

The original controller, shown in Figure 68, was made with the characteristics like that of a Nintendo switch mixed with an Xbox controller. When designing the submarine controller, we wanted to maintain the constraints of what our submarine could do so we made a list of functions to perform and implemented them as need:

- Needs to be able to move forward and backward.
- Needs to be able to spin on a Y axis (turn left and right).
- Must be able to toggle a flashlight but was changed to be variable.
- Needed to be able to release air or water so that it could float, or it could rise in the water at any time.
- Needed to start the air drawing process with the original air design.

Under the listed constraints the submarine controls need to be able to hand and maintain while performing the actions and not be to complex that the user would mess up or get lost while trying to control the submarine.

The last of the original design was the fact that it would need to adapt to a separate power source rather than direct cable power from the battery on the land. With constant discussion we felt the controller should keep a battery to ensure it could become self-powered and not lose any control.

5.7.1. 480*800 5-inch GeekPi HDMI LCD Screen

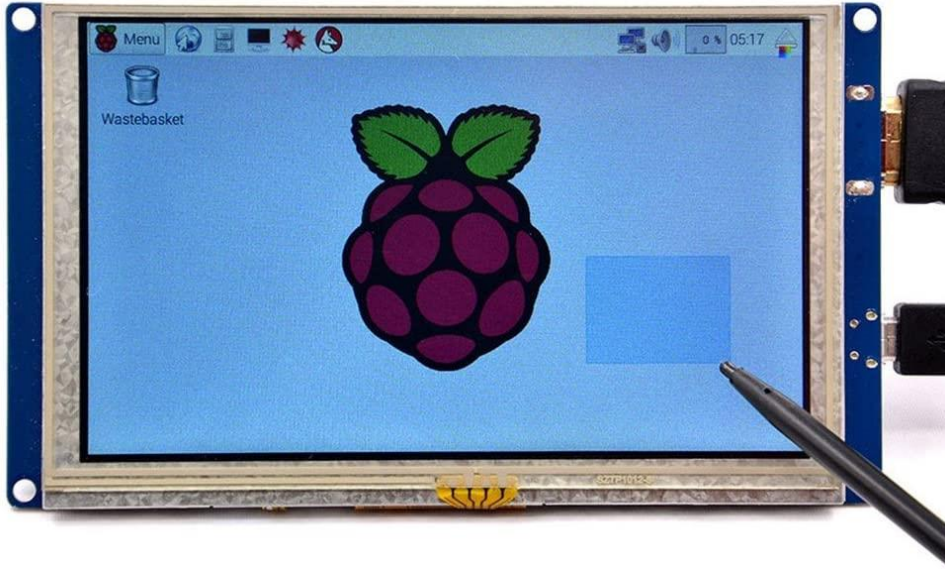


Figure 69: Original HDMI Screen 5inch

The touch screen shown in Figure 69 was considered due to the touch capability and the fact that it just connects using a basic HDMI cable that was easy to shorten or extend when needed. We ended up not choosing this due to space constraints in the controller which would make it much harder to power it individually rather than drawing power from the controller. When looking at Table 16 you can see the price for the screen is relatively close to that of the initially budgeted amount however it exceeded the amount and was not necessarily the best choice just because of its size. The other thing about the display was to run the display the HDMI needed to be a full HDMI cable rather than a simple micro-HDMI to HDMI adapter.

Table 16 GeekPi Specs

Price	\$48.99
Screen Size	5 inches
Power Source	5 V micro-USB
Display type	LCD
Display Resolution	800x480
Interface input	Touch Screen
Weight	4.23 ounces

5.7.2. Raspberry Pi 3



Figure 70: Raspberry Pi 3

The Raspberry Pi 3 model shown in Figure 70 was selected originally due to being the first capable of handling 1080 video streaming along with the capability to decompress live video however was not selected since it might not do it fast enough to fit the live quality we are looking for.

From the listed specifications of the Raspberry Pi, it was noted that in order to use the Gigabit Ethernet it would require a special component to be attached to the device and also the HDMI display wasn't of the quality we were looking for, It lacked the ability to display high end video and without such capability the submarines controller would effectively be playing a native image size for the user rather than the constant desired size.

In terms of the original design the size of the board still matched the desired constraints and would have worked in terms of its physical fittings however the quality of the device needed to be higher overall to accomplish the performance we were looking for with the Pi. The Raspberry Pi model 3 was only capable of handling a small amount of ram which was needed to perform image decryption and process commands from the user at the same time. The Pi model 3 would be able to do the image handling if it were under a lesser load or no time constraint and did not need to be a live feed.

With the over combined capabilities the Pi would be a successful choice just not if the live stream needed to match a higher video streaming quality.

5.7.3. Original Power Bank



Figure 71: Original Power Bank

Anker Portable Charger, PowerCore Slim 10000 Power Bank, Compact 10000mAh External Battery shown in Figure 71 was selected for the ability to power the Pi device while maintaining a sleek design that could fit into the controller. Given the devices specifications in Table 17 it will be capable of powering the controller by itself in terms of an emergency where all power needs to be diverted from the main battery to the submarine.

5.7.4. Power Bank Specifications

Below are the specifications for the battery shown above. Note that the battery is lightweight, and is physically small. This is important in the case of custom controller design, as it dictates the overall size of the controller. If it was larger, the controller would become unwieldy.

Table 17 Power Bank Specifications

Specification/Name	Anker Portable Charger
Dimensions	6.22 x 2.93 x 0.76 inches
Weight	12.08 ounces
Voltage	5 V
Battery capacity	10000 Milliamp Hours

5.7.5. Original 2-Axis-Joystick



Figure 72: Original 2-Axis Joystick

The 2-Axis Joystick in Figure 72 contains two independent potentiometers (one per axis) for reporting the joystick's position, with wiring options for voltage or resistance outputs. This specific analog stick was selected so that it could control more than 1 direction or motion at a time.

5.7.6. Original Buttons



Figure 73: Original Buttons

The Tactile Switch Buttons (12mm square, 6mm tall) in Figure 73 were selected because we wanted a larger size button that would be easier for a user to operate and press. The size was also selected so a user could tell whether it was being pressed accidentally.

5.7.7. Selection and Comparison of Parts

Within the original design the idea was to have the controller be able to make the submarine move up, down, left, right, forward, backward, and have a flashlight.

In this design (Figure 74) the flashlight was going to be an off or on style switch simply because that was what was needed so a tactile button was the solution. The movement for the submarine was going to be split amongst two joysticks and two buttons. The reason for this was because to control the left and right you might want to simultaneously control the forward and reverse motions. The bladder system that was originally designed was going to be controlled by the two buttons allowing a user to press and hold a button to go up and press and hold a button to go down. The larger tactile switches were chosen for this job where of average size but also allowed a user to notice if they were pressing the button or not, so they do not accidentally send the submarine into the ground or on top of the water. The 10000 mAh battery source was selected for the controller because we needed a way to power the controller while maintaining a similar design profile. The Anker battery offered this by being able to fit in the design under the Pi board without making the controller excessively large.

5.8. New Controller model

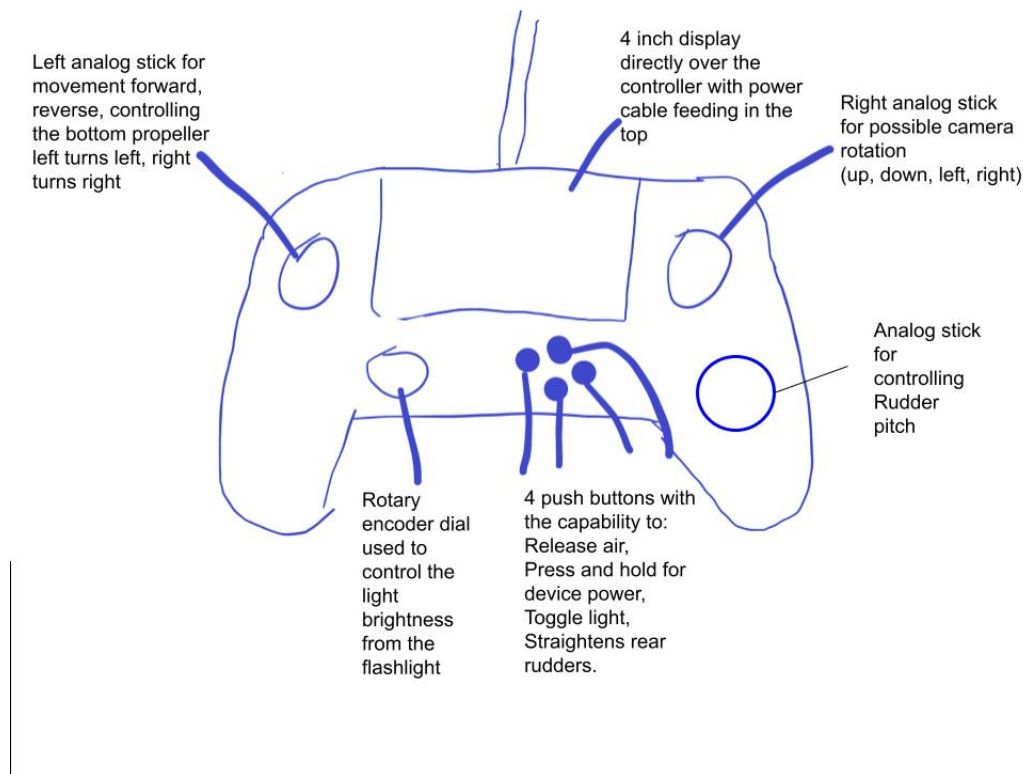


Figure 74: New Controller Model (Created by the Authors)

5.8.1. New HDMI Screen



Figure 75: HDMI Screen

The Waveshare LCD screen (Figure 75) was the selected device for the final design because its specs suited what was needed in terms of power, display, IO and the device was at an affordable price. Given the listed Specs in Table 18, The screen was at a size just about the same as the Raspberry Pi 4 model B which allows us to suspend it above the board in a similar casing style. While in the controller making the larger display fit with the board not rattling would cause unnecessary contacts to the outer controller that would potentially lead to a large heat contact issue that could melt the plastics.

Table 18 Screen Specs

Price	\$38.50
Screen Size	4 inches
Power Source	GPIO or 5 V micro-USB
Display type	LCD
Display Resolution	480x800
Interface input	Touch Screen
Weight	3.20 ounces

5.8.2. Raspberry Pi 4



Figure 76: Raspberry Pi 4B

The Raspberry Pi 4 4GB model B in Figure 76 was selected due to the Gigabit Ethernet capability, HDMI capability and since video compression would need to be performed the ram was increased from the 2GB to 4GB. With the GPIO allowing us to power the display we do not necessarily need to run separate power directly to the board but with the need for the GPIO pins for analog to digital conversion the Display may need to access the USB IO to power the micro-USB on the display. The board was also selected for its known capability of being able to withstand 4k display meaning the image conversion can be made and then compressed to display a higher quality image on the Waveshare.

5.8.3. Power Bank

The Anker Portable Charger, Power Core Slim 10000 Power Bank, Compact 10000mAh External Battery was selected for the ability to power the Pi device while maintaining a sleek design that could fit into the controller. This device is show in Figure 71. With this component the difference between it and its competing parts would be broken down into 3 categories, the price, the size, the amount of power it can output. The component acts as a backup source to supply the controller in an emergency power scenario. With the power being able to maintain a 5V power supply to both the pi and the display therefore making a suitable supply. The reason why the power bank wasn't adjusted between designs was due to maintaining our needs and constraints while being fair with the budget.

Table 19 Raspberry Pi Comparison

Spec/ Name	Raspberry Pi 3	Raspberry Pi 4 model B
Price	\$35.00	\$55.00
Processor	Quad Core 1.2GHz Broadcom BCM2837 64bit CPU	Broadcom BCM2711, Quad core Cortex-A72 (ARM v8) 64-bit SoC @ 1.5GHz
Bluetooth	Bluetooth 4.1 Classic	2.4 GHz and 5.0 GHz IEEE 802.11ac wireless, Bluetooth 5.0
Memory	1GB LPDDR2 (900 MHz)	4GB LPDDR4-3200 SDRAM
GPIO	Raspberry Pi standard 40 pin GPIO header	Raspberry Pi standard 40 pin GPIO header
Output Io	1 x Full size HDMI	2 x micro-HDMI ports (up to 4kp60 supported)
Input IO	4 USB 2 ports 1 x 100 Base Ethernet	2 USB 3.0 ports; 2 USB 2.0 ports. Gigabit Ethernet
Camera Port Type	CSI camera port for connecting a Raspberry Pi camera DSI display port for connecting a Raspberry Pi touchscreen display.	2-lane MIPI DSI display port 2-lane MIPI CSI camera port
Power Requirement	Upgraded switched Micro USB power source up to 2.5A	5V DC via USB-C connector (minimum 3A*) 5V DC via GPIO header (minimum 3A*) Power over Ethernet (PoE) enabled (requires separate PoE HAT)
Weight	1.5 ounces	1.76 ounces
OS loading Format	Micro SD	Micro SD

5.8.4. Raspberry Pi Comparison

From Table 19, the Raspberry Pi 3 was seen to be not powerful enough and didn't have the processing capabilities that were required to compress a 4k image down to a 1080p video file to be displayed on the controller display screen. Aside from the quality of the processor alone being worth the price gap,

the price made the Raspberry Pi 4 a complete upgrade for twenty dollars more, shown in Table 19. With both boards having no analog GPIO there will be a simple circuit created so that the joysticks can be used from the controller.

5.8.5. New Joystick Controller



Figure 77: New Joystick Controller

The 2-Axis Joystick in Figure 77 contains two independent potentiometers (one per axis) for reporting the joystick's position, with wiring options for voltage or resistance outputs. This specific analog stick was selected so that it could control more than 1 direction or motion at a time.

With The 2-axis joystick and the Raspberry Pi 4 the GPIO lacks an analog pin layout so an additional breadboard implementation will be needed to be embedded into the controller. There will need to be an AD to DA converter part as such the KNACRO PCF8591 which would then be connected to the Adafruit MCP3008 and the Adafruit 2028 Assembled Pi T-Cobbler Plus. With these three parts the Raspberry Pi will be able to read in an Analog Input such as the analog stick and convert it into a digital input rather than going through the process of creating a digital comparator and forcing the part to be a digital input and lose the users controllability of the analog stick's movements verse a 4 button D-pad style. However with the change from analog to digital the controller would be more manageable to design and keep shape where the analog requiring other components may cause it to increase in size and become a larger more uncomfortable device.

5.8.6. New Button Choice



Figure 78: New Button Choice

The button in Figure 78 was selected because it can be pressed and selectively keep its source off. Also, this is the size of a quarter allowing the user to easily press it and for the controller to have a proper button spread at the same time.

5.8.7. Rotary Encoder



Figure 79: Rotary Encoder

The rotary encoder shown in Figure 79 has 24 selection options from start to finish. With the larger spread of options, it allows the variable light to have a larger variety of brightness and be able to light up in different scenarios based on the water cloud density.

5.8.8. New Controller Part Comparison

When discussing the creation of the new controller the topic of why each input is needed arose and changes needed to be made. With the current controller design, we felt the direct need to have the capability to control a forward and backward motion was undisputable with a submarine device.

However, the pitch of the Submarine is not common ground for most aquatic toys. The ability to move on a diagonal access in the water would allow the submarine to travel to locations that you could not necessarily float into or move horizontally into it. This would allow the user to pilot the submarine into crevasses and continue without getting stuck. To accomplish this, the idea of adding the left and right motion to the right joystick was created. By adding the directions to the same joystick, we could control the submarine and make it move forward, backward, left, right with one stick and pitch its nose up and down via a rudder-like system with another joystick.

The separate joystick being placed in a way a user can use their thumb on both the forward stick and the pitch stick would allow a user to now control all movements and have more control. Next would be the idea of a camera moving on an x, y rotational axis while inside the submarine. To do this, we decided an additional joystick was needed, one that could control small rotations for the camera on the inside and by using a 2-axis joystick. The user would be able to change the camera view and make it look up, down, left, right by using the joystick moving in the same directions, respectively.

The next design change from the original would be the variable light density flashlight. By adding a rotary decoder, we could control the voltage the onboard light was receiving and in turn make it dim itself for more cloudy waters or maximize the voltage for full light exposure in clear water.

In the terms of the button, we selected the size so that it could fit in a neat patch of buttons rather than being intentionally noticeable. Alongside removing a button for the light, we added a power control, and we also added a rudder straighten button. The power control was added so that a user can easily control the device's power when not needed. Straightening the rudders was also added so that a user could quickly move the rudders to a status ready for moving in a straight line rather than having to manually move the rudders back with possible over corrections.

Overall, most of the changes in components came from effectively compressing the design without causing a performance break just to fit a small form factor design. With the analog conversion parts being incorporated the design would need to now account for holding a wired bread board but with consideration of a D-pad control system being sleeker the users control of the axis is not what we are looking for therefore succumbing to design changes and alterations would be the better option. With the parts the amount or application of each one could be altered later in the designing phase simply because the combination of components can allow for multi functions intern eliminating used space.

5.8.9. Display Comparison

When comparing the displays that were considered for the controller emphasis was placed on some specifications significantly more than the others. The technical specification that carried the most significance with the display was how large the display was. If the display were too big then it would affect the general controller design by displacing where components were to be connected. If it was too small then the ability to see or read the screen would be drastically limited and not efficient. Another spec to consider was the power source, with the 4-inch screen providing the option to power the display using the general purpose output pins. Furthermore, the 4-inch display is cheaper than its 5-inch counterpart for the same resolution. The differences can be seen In Table 20.

Spec/ Name	GeeekPi 5-inch HDMI LCD	Waveshare 4-inch HDMI LCD
Price	\$48.99	\$38.50
Screen Size	5 inches	4 inches
Power Source	5 V micro-USB	GPIO or 5 V micro-USB
Display type	LCD	LCD
Display Resolution	800x480	480x800
Interface input	Touch Screen	Touch Screen

Table 20 Display Comparison

5.8.10. After Demo Controller Update (1)

Many of the smaller components such as the joysticks, buttons, and rotary encoder were not used for the final demonstration. This was due to the discovery that the selected display would use all of the available GPIO pins on the Raspberry Pi 4, without any room for the small components. In order to preserve functionality, the idea of making a custom controller was scrapped in favor of using an aftermarket controller instead. The remainder of the demo controller text after this continues to reflect the before final demo state of thinking until listed otherwise.

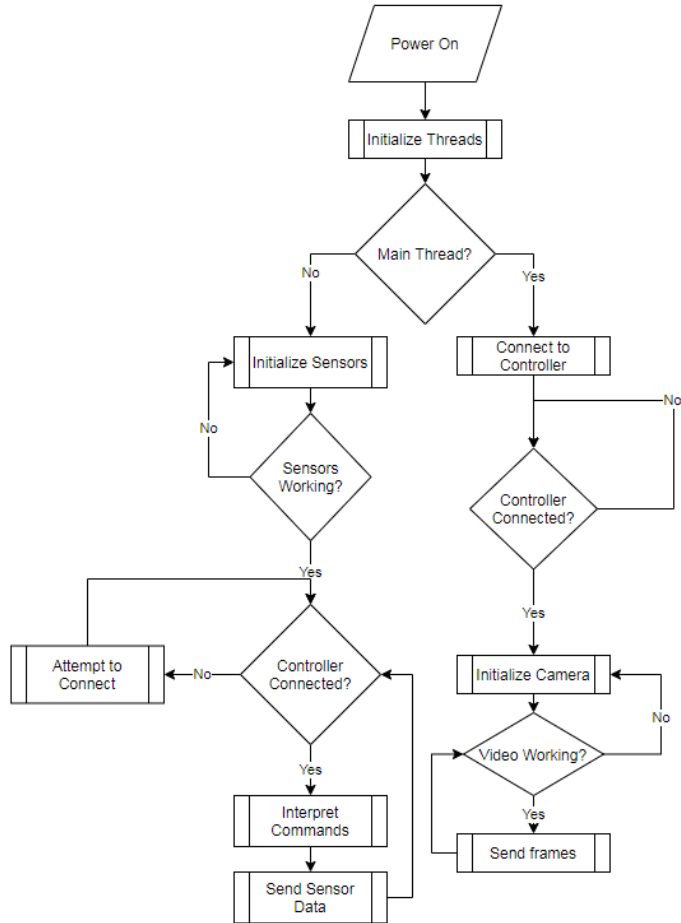
5.9. Submarine Control Program

Control of the submarine is split across two programs: one on the hand-held controller, and another on the submarine itself. These can be written in any programming language or even a hardware description language if a FPGA was used. For ease of development, programs will likely be written in Java, C++, or Python. On the submarine, the program will be run using the on-board computer's Ubuntu based operating system, to reduce resource allocation efforts. Additionally, note that multiple threads will be used to enhance the abilities of the program to transmit data as quickly as possible and to bypass slow or unresponsive code.

To summarize the expected flow of the on-board program (shown in detail in Figure 80): After being powered on, the submarine will establish a TCP/UDP connection with the controller, and use that link to transfer camera frames, sensor data, and submarine commands. During the wait for the connection, the submarine will proceed to initialize the cameras, sensors, and motors in anticipation of the first command. It will then transmit a signal indicating the submarine is ready for use, after which the frames of the camera will begin to be redirected to the controller along with information from the sensors. Throughout usage, the on-board computer will interpret commands sent from the controller, reacting to them by changing the state of the turbines, the ballast actuators, and camera state. For example, the turbines will have their speed and rotation direction controllable.

As part of the controller program is information overlays, this will contain data supplied by the on-board computer. Among the information to be sent are the speeds of the motors, the current depth of the submarine, and distances to nearby objects. If time allows, additional sensors will be considered to improve the experience, such as an internal water detection sensor. Such a sensor would be used to not only detect if water was present, but how much was in the submarine. However, this necessitates the addition of an ADC as the Pis do not come with them.

Figure 80: The general flow of the software to be run on the on-board computer (Created by the Authors)



5.10. TCP and UDP Packets

User Datagram and Transmission Control Protocol Packets serve as the workhorses for the transport layer of the internet. Their use in this capacity, and the fact that many other protocols are ultimately built on top of these protocols warranted deeper investigation into using them for transporting video from the submarine to the controller.

TCP provides packet order maintenance, error recovery, and a maintained connection but at the price of being slower. UDP is faster and more lightweight but discards erroneous packets and has no handshaking protocols. The potential issue of single-bit errors causing incoming video frames to be unreadable, may make TCP seem more desirable. However, it may be more useful to ignore packet errors altogether with the use of UDP, as a packet with several errors could be quickly replaced by an errorless packet. This speed and large amount of space for data per packet may make UDP the choice in the long run, though this requires investigation. At the same time, another investigation must take place regarding whether specialized or uniform structure packets are most efficient.

5.11. After Demo Submarine Program Update

Originally, we had considered splitting the code into classes to make it easier to program and manage. Each class would be specialized for one specific task on the submarine. For example, a sensors class, a camera class, a general Pi class, etc. All components on board the submarine are communicated with via their GPIO connections to the Raspberry Pi.

The organization for the end version of the submarine program dropped the use of classes. Instead, the layout of the end program ultimately was concentrated on developing two C++ source files centered on the functions needed for three threads. These threads are the sensor thread, the command thread, and the video thread as seen in Figure 81. The time pressure necessitated using global variables and magic numbers, but one upside allowed the information to be exchanged and updated faster. However, note that doing these things was not detrimental, as variables are not widely shared between threads.

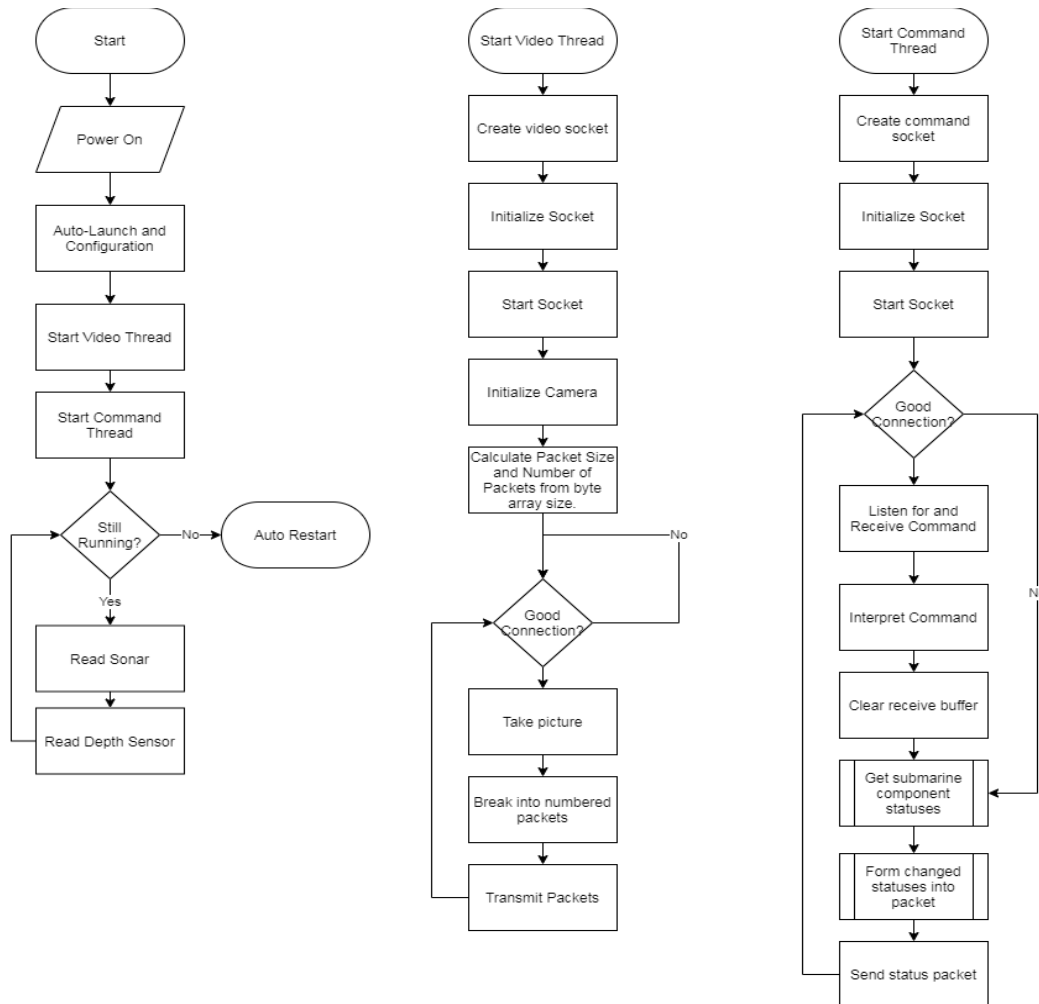


Figure 81: Revised Submarine Program Layout (Created by the Authors)

6. Parts Testing

All parts that are bought require testing to ensure that they work as expected. Each part is checked physically to make sure they are undamaged, and then operated for periods of time to ensure their stability and compliance with their provided datasheets. This is the phase where if something doesn't work as expected, a replacement is required. Below are the steps we took to test that the parts were functional. After each part was tested, they could be incorporated to test the functionality of the whole system.

6.1. Pump Ballast

During our testing for the pump ballast, we realized we should have a method to tell when the ballast tank is completely full. This would be done easiest by having some sort of connector on the top of the expanding ballast tank, and on top of the container it will be in. Having this would cause the connectors to touch only when the ballast container is full and allow us to send a signal back to the user that they are at maximum capacity and depth.

Our initial plan is to design a ballast tank that can hold 300 milliliters of water and will expand upon filling. The HEEPDD pump that we plan to use is able to fill this container fully or completely empty it in just above nine seconds. This is good timing because it will allow us to be more precise with the filling and draining of the ballast. Having the pump run for only 0.5 seconds at a time would allow us about 18 instances of running the pump before it gets filled, and we reach maximum depth.

6.2. PCB

After the PCB is designed, printed, and built, we will test the PCB by attaching the power cord into an outlet on the board that is on land. Then attach the RJ45 Ethernet cord to the on-land PCB. We will measure the voltage and current out of that Ethernet cord. Hopefully, those values are what we expect them to be. If they are, then we will run the same test on the other PCB, which will be inside the submarine. After both of those tests pass, we will attach the Raspberry Pi and controller that will be on land to its corresponding PCB and test the communication signals coming through the Ethernet cord. If those signals are correct, then we can attach the submarine's PCB to the Ethernet cable. After we connect that cable, we can now attach the submarine's Raspberry Pi to the PCB and test the signals coming through the system. If the signals are received and transmitted correctly, we can then test the voltage that would be going to all of the other components, such as the headlamp and the propellers. We must do this test before we attach any of the components to ensure that we don't harm anything. None of our other components are necessarily cheap, so burning them up would not be a good idea.

6.3. Regular Raspberry Pi Camera Testing

The Raspberry Pi camera module must be tested in several ways to ensure that it is working. While the camera module is a very common item and only has the purpose of recording video, there have been cases reported where they were damaged during shipping or broke after a few days. The simplest thing to check is whether it can take still images, and this can be accomplished by running the command “raspistill”. This simple test could fail in a few ways, such as the camera having a loose connection or if the device is not enabled as part of the Raspberry Pi OS configuration.

Should the still image test succeed, the next would be to see if video can be recorded by running the command “raspivid”. If that also works, more advanced tests can be carried out. We would test in a variety of environments, such as low light areas and murky waters. Following that would be a test of the transfer speed between the camera and the controller. This requires ensuring all necessary connections have been made and that slowdowns elsewhere in the submarine control program don’t affect the performance of the camera. After that, latency tests will be conducted to check if the performance is acceptable.

6.4. Raspberry Pi and Module On-Arrival Testing

Upon arrival, the very first thing to be checked was if each of the components could be turned on. Due to the camera and pan/tilt mechanism relying on communication with the Raspberry Pi, it needed to be powered and given an operating system. The Pi itself does not come with an operating system, instead needing to be given a flashed SD card. Setting up the operating system for use was based on following the instructions provided on the website of the Raspberry Pi foundation. The operating system can be seen in Figure 82.

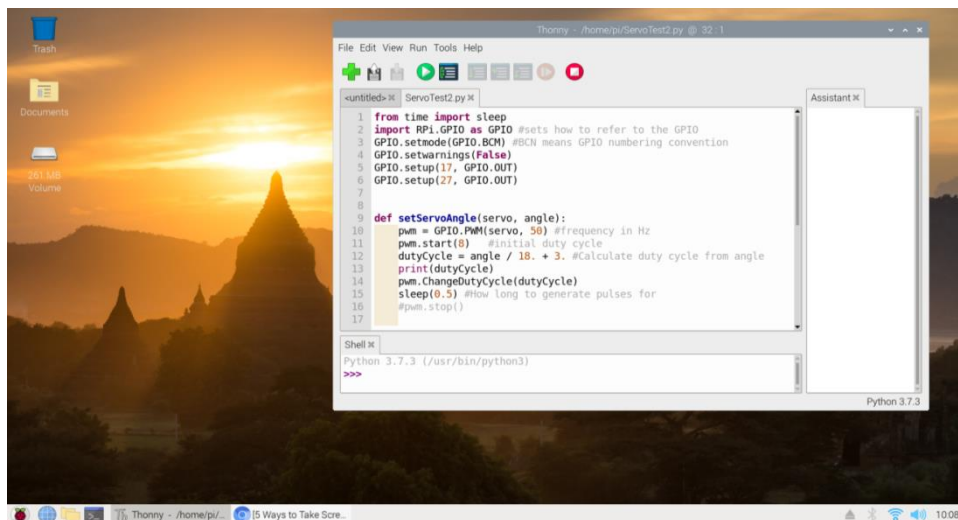


Figure 82: Raspberry Pi OS (Created by the Authors)

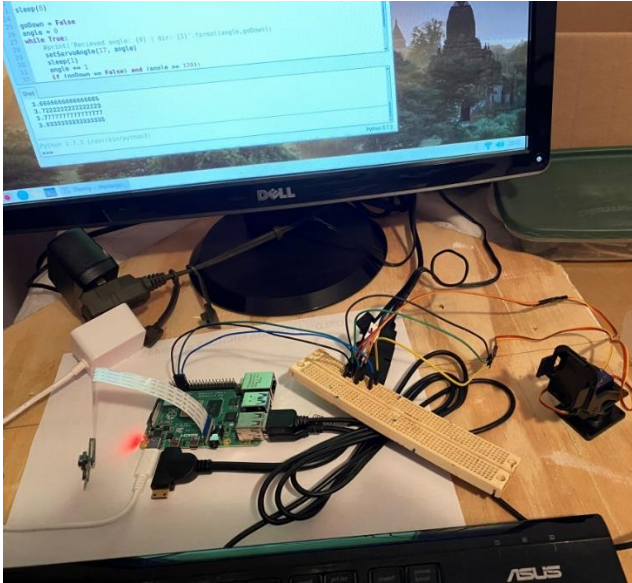


Figure 83: Camera and Pan/Tilt testing environment (Created by the Authors)



Figure 84: Unoptimized first test picture (Created by the Authors)

Figure 83 and Figure 84 show the environment available to test the Raspberry Pi camera module in. The operating system comes with a pre-installed Python integrated development environment called Thonny. Thonny was used to test the pan/tilt mechanism, whilst bash commands were used to test the status of the camera. Figure 84 is the first picture taken with the camera, though it should be noted that the commands came with a large variety of possible input parameters, which were not optimally used. Proper settings could improve the image quality.

6.5. Code

To test the code, we will attach the propellers to their PCB and attach the voltage to this PCB as well. When one person pushes the joystick, we make sure that the correct propeller is moving according to the code. If not, then we modify the code and retest. We follow the following tests:

1. When the joystick is moved up, only the bottom propeller will work and the motor attached to the syringes will move to allow water to be pushed out.
2. When the joystick is moved down, only the top propeller will work and the motor attached to the syringes will move to allow water to be pulled in.
3. When the joystick is moved in the forward direction, all motors will move full speed ahead.

6.6. Propulsion

The first thing we will do to test our propulsion system is to have one person hold the four propellers while another person applies voltage to all of the leads. This test will make sure that all of the propellers are functional and are spinning in the correct direction.

Next, we attach the Raspberry Pi to the propellers to make sure the right propellers are working with those signals. We also need to make sure that the propellers work after the power has gone through the voltage regulators. If any of these tests fail, we need to fix the issue, and retest.

We will test our thrust vector system by checking to make sure that it tilts in the correct direction to aim the motors in corresponding direction.

6.7. Battery

We will test our battery by running at full force with our entire expected load and seeing how long it takes for the battery level to go down below ten percent. We will run this same test ten times to make sure that our number is accurate. We will then compare this number to the expected battery life calculated by the amount of current being pulled when the load is being run.

The next test will be to see how long the battery will run when the load is not run at full throttle, but with nominal values.

The last test we will run will be to see what happens when our battery dies and make sure our default settings run correctly.

6.8. Waterproofing

To test waterproofing, first we will put each individual component that will be submerged into a bowl of water, such as a sink. If that test passes, then we move on to putting all of the parts into/onto the housing. We attach the parts with the Marine weld epoxy but at first leave the Go Pro off so we can see if any parts with the marine weld leak and take on water. If any water gets inside, we fix that and try again.

Lastly, we put the Go Pro in its hole and put the entire submarine in a bathtub. If everything goes smoothly with this, then we will test our entire submarine in Avery's pool. Avery's pool is pictured below in Figure 85 and Figure 86. The idea of testing in the pool allows for the control of minimal environmental effect should testing go wrong and require an abort. The pool test would be first of many water tests to ensure the sealant has the capability to withstand the drying after use to then be submersed again.



Figure 85: Avery's Pool (Created by the Authors)



Figure 86: Avery's Pool at Night (Created by the Authors)

If everything goes well in Avery's pool, then we will test it in Lake Claire, as pictured below in Figure 87, to see if the lake water has any different effect on the submarine. Should the lake water tests prove successful, night-time or otherwise dark conditions will be used to test the headlight. Daylight dark conditions can be simulated by bringing other objects into the pool or the lake for the submarine to be piloted into or near.



Figure 87: Lake Claire (Created by the Authors)

6.9. Headlight

The headlight's waterproof testing will be done as described in the waterproofing section. To test the headlight's functionality, we will be testing it first in Avery's pool at nighttime. If the test proves to be successful, we will also test it in lake water at Lake Claire (pictured above) as well as the ocean water at Jetty Park Pier pictured in Figure 88 below.

Figure 88: Jetty Park Pier with departing cruise ship (Created by the Authors)



Running tests at Jetty Park act as the ultimate proving ground for the design and features of the submarine. The existence of the beach and running tests there will make the results of the trials very similar to the average expected use case. There are a lot of rocks as can be seen in the picture, with some that extend well below the surface of the water to form many little crevices. Such crevices are a common hiding place for fish and would prove a good place to test the camera as well as a test of the headlight for searching deep within the rock formations for the shier wildlife. Jellyfish are also known to live in the area, so the presence of local wildlife would prove a good test of any propeller coverings put in place. The crevices are also very sharp and should act as a good test for the general wear and tear from hull collisions.

6.10. Controller Design:

The prototype controller layout stems from the general design of what you typically see game consoles using now. However, the key difference being that of a 4-inch centralized display that will be used to display the livestream feed of the submarine, a feature that's uncommon on current console generation controllers.

The original design of the controller maintained the simplistic idea of 3D printing a controller capable of just housing the Raspberry Pi and display however with changes to the Pi that was being used and altering how the display will be situated in the controller the design needed to be altered. Finding a display that would let us rest it over the Raspberry Pi would allow us to hollow out the center of the controller like a basin and rest the two components inside and have the handles of the controller contain a board and the other components.

An issue that arose while testing just the Raspberry Pi and the display alone was the issue of heat. The Pi and display were putting out a large amount of heat which could potentially melt the 3D printed plastics or possibly short circuit itself due to overheating. Another issue with a large amount of heat would be endangering the user if they were to use the controller for a prolonged time. Proposed solutions to the heat issue alone would be lining the internal basin with a heat resistant padding that could allow for it to just grow to a warm state without passing heat to the plastic. In terms of a design perspective this would be a simpler alternative however does not solve the issue of the Raspberry Pi overheating and would possibly cause malfunctions.

The second solution that was formulated was to extend the middle basin out in terms of depth and connect a fan under the Pi and draw hot air out from the board and pull cold air through over the display and board. By increasing the basin size, we could place it under the Pi and still in a plastics casing designed for letting air pass through without impediment. This process solves both the issue of the plastics becoming too hot and the issue of the board overheating. However, this increases cost and creates more moving parts inside of a device not typically known for having a fan.

6.10.1. Configuring the Controller Pi:

When first receiving the Raspberry Pi there is not typically on it unless you specifically purchase a model that is preloaded which we did not buy. So, for the first course of action, we need to install a software OS onto the Raspberry Pi. For both of the Raspberry Pis the recommended software was the Raspberry Pi OS from the official Raspberry Pi website and imager installer (Figure 89) [50]. To install the software, we needed a micro-SD card that was formatted to a FAT format which required additional software to initialize the card. Once the card was initialized, we then installed the Raspberry Pi imager software which would be downloaded and unzipped on the SD card. With the downloaded files we then select the OS and remove the micro-SD card to extract onto the Raspberry pi.

Figure 89: Raspberry Pi setup



Once the Pi has an OS to operate on, we need to create software for the Raspberry Pi on the submarine to communicate with the Pi inside of the controller. With the Pi on the controller, we need to go through an additional process before being ready to run the software.

Because we are going for a keyboard mouse less design for the controller, we needed the touchscreen display to be capable of controlling the Pi which required a separate software and additional set of parameters. When initially connecting the 2 components the screen worked but not touch, so we had to go into the configuration file and add a few lines of code that set the HDMI timings and the overlay visual changes. Once the config file was altered, we then had to download a clone onto the board software that would allow the touch and sensitivity controls to work properly.

Once touch was activated the Boards would both be loaded with a software that would boot up at launch that ran the connection through the Ethernet. This would allow the boards to send signals to one another within a set packet length and allow for the live imaging to be sent to the display using the Pi's own screen. The

user may end up having to launch the software using the touchpad so within the controller there will be a small portion that contains a stylus pen in order to interact with the screen.

6.10.2. Controller Layout:

With the Raspberry Pi being notably in the center the rest of the controller needs to be framed in such a way that a user can access every command or button without changing eye position too much. This would allow a user to look at the component that they are using without advertising their attention or eyes off the submarines viewing stage. This is simply a safety concern we felt that needed to be implemented and upheld since we are trying to appeal to a variety audience.

With the location of the screen in mind we felt that the analog sticks being located towards the top of the controller would allow for a user to grip the controller well enough to use and no struggle to reach while holding it. The reason for making sure a user had complete control was if the controller fell while a user was trying to use it the movement analog sticks may end up breaking in an active position sending the submarine into a possible collision, however this scenario is being planned to be handled using a ultrasonic sensor that can shut off the board should it reach a dangerous distance to an object whether it be an animal or wall.

After the analog placement we needed to worry about how to install the buttons inside the controller. With the current buttons that are being used we can make a hole for the tactile button to come up through the controller or we can use a separate part that would press the button while it is inside of the controller. The current design suits more of the raised button idea and has a separate button press down on the actual component.

The last part design we needed to incorporate into the controller was the rotary dial. The dial would need a space in order to be raised up through the printed controller and allowed space to rotate in order to adjust the light output. Given the size of the dial the actual controller will need a more recessed space so that the dial is not poking too far out of the device.

In order to connect all these parts there will be an embedded bread board that will rest inside the controller print and under all the components so that they can be set in a sturdy position and wired to the Raspberry Pi without worry of a wire coming out or disconnecting during transportation or use of the controller.

6.10.3. Controller Communications:

In order for the Raspberry Pis to be connected the software design that will most likely be used will be the UDP or TCP connection system. We will make one Pi the lead controller that will have an output port selected that will contain message packets of outputs that will then be received by the submarine Raspberry Pi using the same port.

The submarine's Raspberry Pi will then have a server port that will be specifically designated for sending an output with a receiving port being set at the controller side. This is where the submarine Raspberry Pi will be turning the live camera feed to a compressed data set and then sending to the controller where it will convert the data set to the live camera display. The controller will do a similar system where it will convert the buttons and analog controls to a data packet to be sent over the Ethernet port to be received by the Raspberry Pi. Once the Pi receives the data it will convert it to the action to be performed and will send the signal to control the motor that is being used.

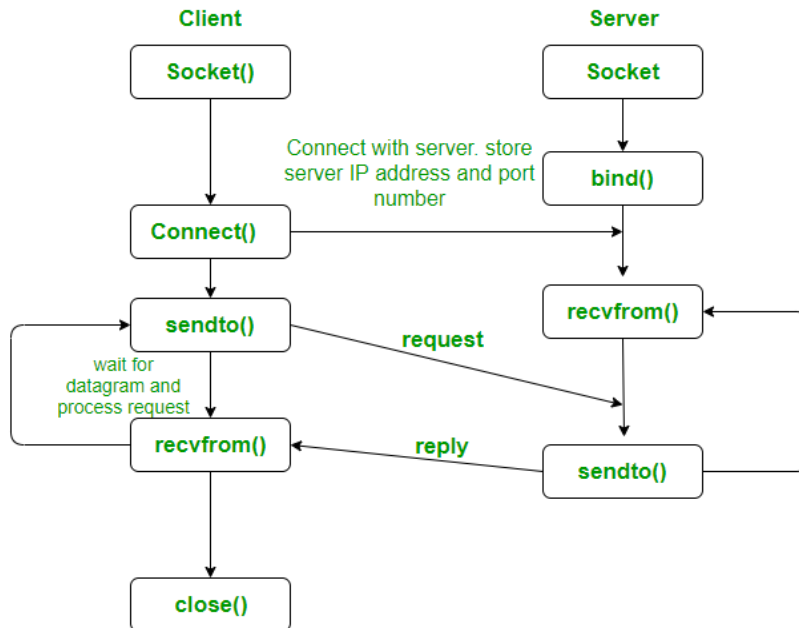


Figure 90 Controller Connection

In Figure 90 you can see both the client and the server starting their communication function which translates to having the submarine and the controller running the start of the communication function. Once they are both started up you must have the controller try to bind itself to the submarine Via sending a connection function to which the submarine replies its binding function. Once the two have been connected the process of transferring info can occur. The info that would be sent would be a request from the controller to get images the submarine is capturing. At the same time, the submarine would be sending requests to get a command such as movement and reply back to the controller showing it moved through images. Due to the fact of needing both a request and reply the client server system will need to be modified tremendously.

6.10.4. After Demo Controller Update (2)

As mentioned in the first part of this update, the custom controller was replaced with an aftermarket Xbox controller attached via USB to the controller Pi. A

custom controller was not implemented in order to maintain touchscreen functionality. The resulting setup is shown below in Figure 91.



Figure 91: Final Controller Setup (Created by the Authors)

6.11. Umbilical Storage:



Figure 92: Cable Wheel

By using the reel such as the one in Figure 92 along with joining the battery device to it we will be able to both store the Ethernet wiring along with being able to draw in the submarine should it be rendered immobile or otherwise necessitate retrieval. With the use of the tether, we allow the user to be able to retrieve the submarine in a safe process while remaining out of the water. The protocol for this would simply involve powering down and cranking in the wire till the submarine reaches the bank or edge of the submarine and then pulls it from the water.

By attaching the battery to the rotary wheel, it will allow it to be sturdy and stay still in different weather conditions rather than a free-standing plastic. The battery being attached to the reel also allows for simple deployment anywhere. The user would need to establish a launch area and to then unreel the submarine from that location till you reach the desired distance. The housing for the wire storage was alternatively a hose bin where the user would be able to move the battery and wiring and be able to use it as a seat rather than the user needing to stand or bring their own. However, the compromise to this would be the weight. With a variety of user pools moving the bin for disabled would be much too difficult so allowing a smaller lightweight device would be much easier.

7. Prototype Testing Plan

The below section details the plans that were initially thought of in order to test both the software and hardware components of the submarine. As the development of a submarine is complex, and requires many parts to work correctly, plans must be developed to test the parts above in a reliable and informative fashion.

7.1.1. Hardware Testing Environment

In order to test the prototype appropriately and thoroughly the best way would be under 3 separate environmental conditions. The conditions that would be best would be an out of water condition, a controlled water condition such as a pool or small pond, and the last environment to test in would be a natural spring or ocean. With the variety of these conditions, it will show us whether or not the submarine will be able to withstand increasing water pressure along with propelling itself in the water if it varies in conditions.

With the first environmental condition we test in being the out of water environment this would allow us to test the connection of the Pi's onboard the submarine and in the controller, it would also allow us to determine the inputs of the controller vs the output you see occurring in action. Out of water environment allows for the devices to function with no impediment and demonstrates the power usage from the submarine with idle usage and running at a base state.

The second environment that would be used to test the prototype would be a pool or small pond. The reason behind this would be to determine the submarine's power with little to no extra resistance besides the water. The depth would be enough to detect any body leaks or wire issues without completely compromising the submarine in the environment. Being in a pool the retrieval of the submarine should be simple during a catastrophic failure.

The last environment that we would run the prototype through would be a spring or an ocean. Exposing the submarine to varying water conditions allows us to benchmark its performance in a rougher moving condition such as under waves at a beach or in a depth check using a spring. These conditions also create the possibility of wildlife interaction to which we can see how a fish or other aquatic creature reacts to seeing the robotic submarine. The condition of varying the water allows us to also check how the motors and any moving part reacts to different acidities and densities.

7.1.2. Hardware Specific Testing

To test specific parts of the submarine we will be putting it through the same trial in each of the three environments. By maintaining a constant test plan in each of the environments we can see how the water or general pressure affects the performance.

The best way to test the hardware as a unit on the device would be to put the submarine through time trials repeating a similar course multiple times and determining the averages of the trials. Trials could be as simple as going down to one end of a pool and back or seeing how long to get an item displayed on the screen or similar trials as such. Some of the Trials examples are these below.

Trial examples:

1. How long can it last on the full charge battery idling in a neutral position, essentially just being turned on in the water or air.
2. How long does it take for the submarine to travel over a 5-10 meters distance
3. How long can the submarine last while constantly running the motors.
4. How long does it take a submarine to go a distance, turn and return.
5. How accurate is the live streaming capability given size of cable and depth.

In the trials above we felt they would be the best way to determine if the submarine is capable in all environments or if a specific environment could be dangerous and adapt to allow the submarine to perform in that environment. With tests involving distance the longer or farther the submarine must travel the more valuable the information becomes. If the submarine is only tested using a smaller distance, then the environment of the water would be less deterministic where if it must travel a distance the environment a large space to cause the submarine issues has.

7.2. Controller proof of concept



*Figure 93: Controller Proof of Concept
(Created by the Authors)*

The image of Figure 93 is displaying how the micro display would be embedded similarly to the real controller. The process of housing the display in a fixed

position while maintaining a similar inner storage reservoir. There was also an additional fan installed so that the air circulation could flow across the board and cool down the Pi.

7.3. Software Testing

While testing the signals of the TCP or UDP connection we will connect the Pis using the Ethernet I/O but also connect a monitor to display the code terminal and track the packages as they move through. This method would be the most optimal for tracking the simple commands such as the button commands or a power on or off.

To test the software, we plan to initially start with a simple detection program that displays the x and y rotation angles of the analog sticks to determine which speed and direction the submarine propellers should follow. While detecting that we can also send the signals for the buttons and dials using the same process of just the Pis without directly powering the submarine. This way would ensure that the signals being sent are correct and accurate without the possibility of straining or damaging the motors.

For the LED headlight, we will first ensure that it can be turned on via the push buttons. When determining the rotary dial signal, we will establish values for each of the positions of the dial and send that signal once the dial reaches that point. It will repeatedly send this signal to ensure the light maintains that brightness setting. We will then rotate the dial through several full range sweeps, to ensure that dynamically changing the light operates correctly.

Additional software testing can be carried out by testing the responsiveness of the pan/tilt mechanism to the controller's dedicated four-axis joystick. At first, random inputs will be given from the joystick to determine if the mechanism will react at all. If this fails, investigation will occur via the aforementioned monitor with the display terminal. In that case, a keyboard will be attached to the submarine Pi for attempting an override and to fix the issue on-site.

Should control be established, pure panning motions will be used first. This will be done at a constant speed (from the pressure on the joystick) at first, and if the panning occurs as expected, variable speeds will be tested as well. Similar testing will be conducted for the tilting part of the mechanism.

More importantly for the pan/tilt mechanism is the smoothness of being able to track an object. Since this is a primary goal for the mechanism, it is important to test how smoothly we can track a path, so we will move different objects in front of the camera and task the operator with following it. If the panning and tilting are too sluggish, adjustments will be made accordingly.

7.4. After Demo Overall Testing Update

Given the scope of the project, the amount of parts and software to test is large. Additionally, since many of these parts needed to be tested together as sub-assemblies, this update will only focus on the testing performed on a case by case basis. More specifically, we will focus on the pan/tilt, ballast, and engines. Due to their simplicity, code, PCBs and PoE, and smaller components such as the sensors will not be discussed. While steps above may have been followed, they were treated more as a guideline for testing rather than a strict protocol.

7.4.1. Revised Pan/Tilt Testing

The pan and tilt mechanism was originally to be controlled via commands on the left joystick such as “Right_Joystick 1” with the number indicating the direction to look. While coarse control was easy to develop, fine control was not, so this part of the command structure was scrapped. Instead, this was replaced by sending the x and y coordinates of the right stick, and directly mapping it to the servo power range of the motors. This worked better and was used in the final demonstration.

7.4.2. Ballast Testing

The only ballast that could be tested outside of the water was the dynamic ballast involving the valve, pumps, and bladder. The static ballast (the rebar mentioned earlier) could not be tested until the final demonstration due to access and time scheduling issues. As for the dynamic ballast, all the parts were connected using the flexible piping and controlled via the on-board GPIO.

With the small inlet pump, this part proved unable to even suck up water in the enlarged system. The environment for testing for the final demo was larger than the one for the midterm demo, and thus had too much air resistance internally. This necessitated replacing the pump as mentioned before. However, after replacing the inlet pump, and various debugging attempts the system was able to inflate the bladder at the press of a button and deflate at the press of another button. Due to the differences in the small and large pumps, the large pump can surface the submarine much faster than the small pump can sink it. The pre-demo testing environment is shown below in Figure 94.



Figure 94: Ballast testing environment (Created by the Authors)

7.4.3. Engine Testing

The engines could be tested as soon as the PCB was finished. Individually, each motor worked well, but were overwhelmed past 2.5 A of current. Once all four engines were wired to the board, it was a software effort to make sure appropriate duty cycles were given to them, and that the appropriate direction was determined for the left stick. Much like the right stick, the originally proposed command was not used due to the difficulty in programming fine control. Power was directly converted from the x and y position to a servo value using a mapping function. After debugging efforts, pulling the left stick back reversed the submarine, pushing forward made the submarine move forward, and similarly for the left and right directions.

7.4.4. Three Demonstrable Specifications

The three demonstrable specifications were easy to test. The pan/tilt already constituted one such specification. Testing of the others – time delays between input and reaction as well as delay between frame sending and receiving were also easy. So long as a UDP packet contains the start time, the receiving end (either for command or image) could do the math and determine how much time passed since when it was sent. However, one noticeable drawback of using the system clock was that they were dependent on the last time they were connected to the Internet for accurate time. The internal clocks on the Raspberry Pis do not update until they connect, meaning that they always use the time they read when last turned on. This further means that should the Pis be desynchronized, the time delay measured will reflect this, so being off by even a minute can drastically increase the measured delay. To reduce the effect of this, before measuring, both Pis were turned off. After this, they were both simultaneously turned on and then connected to the Internet to read the time. This had a dramatic impact and made reading the time delay much more reliable for both measurements. Example measurements are shown below in Figure 95.

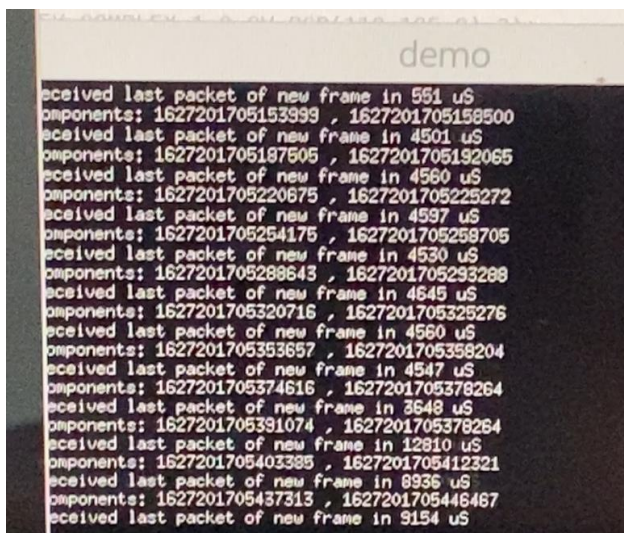


Figure 95: Test frame measurements (Created by the Authors)

8. Standards and Constraints

The following chapter discusses the standards that will be investigated over the course of project development. While time may not allow for the investigation of all of them, having standards to use will enable the safe interaction of parts together and an easier time assembling everything since the parts will have predictable behavior.

8.1. Standards

Standards exist to describe the behavior and properties that a product will conform to, as well as how two products should interact with each other. Due to being composed of several existing products that follow standards, along with the existence of law related standards, our solution will be subject to several engineering and environmental standards. The following section details the various standards that influenced the design of the ROV, applied from the water's edge to its depths. Several additional standards have been identified for further investigation during implementation including:

- Ingress Protection Codes (IPX)
- Universal Serial Bus (USB)
- High-Definition Multimedia Interface (HDMI)
- Category 6 Cable (CAT6)
- Real-time Transport Protocol (RTP)

8.1.1. Restrictions on Hazardous Substances

While the RoHS is an EU directive as opposed to a standard itself, it nonetheless encompasses several product standards on substances used in electrical and electronic equipment. More specifically, it requires that heavy metals and specific flame retardants be replaced with environmentally safer alternatives. Since 2011, manufacturers have also been required to show product control related documents proving that no restricted substances enter the European market. Starting from 2019, Cadmium has had a limit of less than 100 ppm, and 9 substances have limits of less than 1000 ppm. This includes:

- Lead
- Mercury
- Hexavalent Chromium (Cr VI)
- Polybrominated Biphenyls (PBB)
- Polybrominated Diphenyl Ethers (PBDE)
- Bis(2-Ethylhexyl) phthalate (DEHP)
- Benzyl butyl phthalate (BBP)
- Dibutyl phthalate (DBP)
- Diisobutyl phthalate (DIBP)

This in effect means that most if not all parts ordered will be RoHS compliant, due to being involved in European markets. This can be determined by the green checkmark associated with the RoHS European Conformity (CE) marking directive established as part of RoHS 2. This would make our product more RoHS compliant, although we still need to check that our parts are compliant, and we would still be required to produce supporting documents if we wanted to sell this as a product in Europe.

8.1.2. Basics of Pulse Width Modulation

Pulse width modulation is a technique for delivering energy through continuous discrete pulses as opposed to an analog signal. This can be done by changing the duration (the width as seen on an oscilloscope) of the high and low pulses [52], and the ratio of high time vs low time defines the duty cycle of a digital signal. See Figure 96 for an example of duty cycles. Given enough bandwidth and bit resolution, any analog signal can be encoded using PWM. PWM is a widely used technique because it drastically reduces power dissipation. When the signal is logically high, the switch has low resistance and a high amount of current, whereas in the logical low state it has a high resistance and near-zero current. Additionally, analog motor controllers are inefficient due to the requirement for substantial voltage drops and substantial current to be effective.

In our application, pulse width modulation will be used to control the motors, as well as other components from the Raspberry Pi. PWM also provides increased noise immunity, which is an important property when using serial communication methods such as I2C.

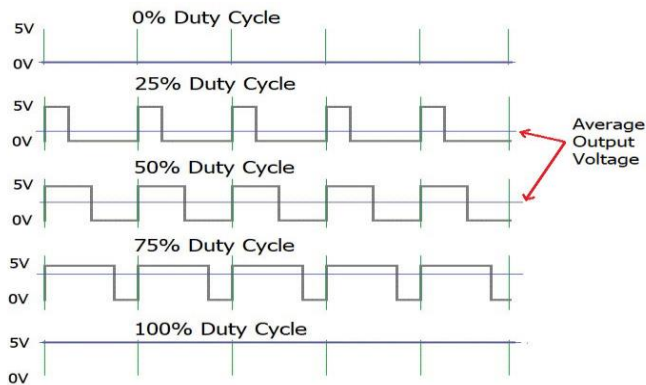


Figure 96: Pulse Width Modulation

8.1.3. Inter-Integrated Circuit

The Inter-Integrated Circuit (I2C) serial communication bus is a de facto standard used in many microcontrollers and add-on modules. It is a way of connecting multiple lower-speed slave circuit chips to one or more master processors. It uses two wires for short distance bidirectional communication, and typically connect modules such as data converters, driver circuits, and sensors. Signals are generated using pull-up resistors and pull-down FETs.

8.1.4. IEEE 802.3bt

As part of our use of Power over Ethernet, considerations must be made about how much power can be transmitted due to the line. We had initially considered the use of cables that use the 802.3at standard, however, due to the power consumption of the devices on board the submarine, we swapped to cables that implemented 802.3bt instead. Created in 2018, the Institute of Electrical and Electronics Engineers defined amendment 802.3bt to “utilize all four pairs in the specified structured wiring plant”. This represents a significant change and was used to “solve the problem of higher power and more efficient standardized Power over Ethernet delivery systems”. The updated standard introduces two additional levels of power over its predecessors: Type 3 which supplies 51 W with 600 mA, and Type 4 which supplies 71.3 W with 960 mA.

8.2. Constraints

There are several constraints that must be considered for a submarine, ranging from its design to its use. How the submarine is laid out, who uses it, and the environment that it is used in contribute to such constraints.

As part of the design process, we are affected by the COVID-19 global pandemic which constrains our abilities to meet in person as well as the ability to order parts. During the summer months however, meeting in person can be undertaken more freely due to the age restrictions for the vaccine being lifted on April 5th for all Floridians 16 years and older. While the vaccine has become available, global supply chains have mostly recovered, and some on-campus classes became available as of the 2021 spring semester, meeting online and part delays are still to be expected. Even though part estimates are more accurate since a “new normal” has been established for most manufacturers, these parts are still likely to take longer to arrive than pre-pandemic speeds due to extra measures that may slow down the process.

Another constraint discussed briefly before is the use of our own money to fund the project. This comes from the desire to reduce additional constraints that may be imposed by sponsors and to keep control over the project once design is complete. Even if we did use sponsored money, achieving a working prototype within the collective budget described below is important, and as such research must be thorough to avoid buying incorrect or unnecessary parts. We also wanted for this product to be commercially competitive despite it being a prototype, meaning it could not cost that much more than a pre-existing product.

In terms of the local environment, preventing the destruction of the environment the submarine is placed in or its inhabitants is important. Propellers must be surrounded with a mesh to avoid hurting nearby fish or human hands handling the sub. The umbilical cord must be thin enough to avoid harming coral reefs. During the manufacturing process, care must also be taken to avoid the creation of waste from the sub, such as plastic particles from a poor printing process or

parts breaking off and being left behind. Additionally, if any large assemblies break during manufacturing and assembly, this would create waste that can't be easily recycled. Compliance with environmental standards should also be followed whenever applicable and possible to follow.

Another set of constraints to consider are safety constraints. The design of the submarine should have the ability to include coverings for the propellers, as these would be capable of harming human hands if nearby. The electrical wiring of the submarine and batteries are also something to consider, especially because of the large voltages and currents required to overcome the internal resistance to the Ethernet cable for Power over Ethernet. Should wires become loose, or electrical contacts become exposed, there is a high risk of electrocution and possible death. The design must include ways to mitigate such risk.

Additional manufacturability constraints include the requirement that all non-waterproof parts must be kept in sealed sections of the ROV. The hull must withstand the pressure at the depths of the body of water being explored. The depth of the submarine must be strictly controlled and monitored to avoid crashing. The weight of the submarine cannot be heavy to one side, as this would create a tendency to tip or roll, and risking it sinking. The motors must also be placed in an optimal location to allow the most control of movement.

To be sustainable the submarine must be designed in a way that avoids the need for constant repair or servicing. The batteries used for the submarine and controller should be swappable or rechargeable which would minimize down time. One possibility for our design would be making it possible to swap cameras. If the camera is damaged, unresponsive, or provides poor quality imaging, it should be possible for the user to change it easily. Making the LED accessible and replaceable has also been considered.

Overall this leaves us with the following notes: meetings should be kept virtual until part assembly or testing is required, parts must be ordered ahead of when needed due to the lingering effects of COVID-19 on global supply chains, parts must be thoroughly researched before purchasing, the end price must be competitive, debris can't be left in the environment - parts must be thick enough to not break, the submarine must be well balanced and durable, the submarine should have swappable parts, and high current areas should be isolated.

8.2.1. After Demo Constraints Update

While some constraints – such as the money, environment, and COVID had their notes above followed, some others were not such as the need for swappable parts and non-exposed propellers. While for a prototype unprotected propellers are okay due to final testing only taking place in the controlled environment of Avery's pool, a production ready submarine would need this issue addressed. Additionally, constraints such as scheduling issues among team members was not previously identified, and is one that must be considered for future projects.

9. Submarine Body

As part of the aesthetic and functional aspects of the submarine design, the body of the submarine is what will be seen by the user when not looking at the controller view. The body must be capable of resisting the pressure at the target depth for sustained periods of time, and able to sustain several minor impacts. The body must also have some purposeful holes where valves and other interfaces will be added. 3D printing has been considered for making the body, although the cost of printing even a portion of the hull would be significant unless the submarine was designed with a small size in mind. A smaller size would reduce the natural buoyancy of the submarine, and the chosen ballast method would be more effective as a result.

9.1. Pressure Calculations

As previously said, a major part of the design of the submarine is the ability for it to withstand pressure underwater. This is especially true for the viewport that the camera will see out of, because the viewport will be the largest purposeful hole in the hull and its greatest possible point of failure. This point of failure comes from the different materials the window and hull are made from, and their different compressive strengths. However, a good choice of material makes this less of a concern. Underwater structures and vehicles are often made with acrylic glass, and these have been known to survive at the target depth and beyond, along with also being scratch resistant. Determining the appropriate thickness of the dome is based on the kind of pressure that it can survive in. Depending on the formation process, the thickness of a manufactured dome can vary greatly from near advertised thickness at the sides to only 25% thickness at the top [9].

The acrylic will be a half-dome that's open to the air inside the submarine. As a full material analysis including the uneven thickness of the dome is outside the scope of this project, the classical equation [7, equation 1.1] for a complete elastic thin spherical shell the dome can be represented by the formula below:

$$P = \frac{2 * E}{\sqrt{3 * (1 - \nu^2)}} * \frac{h^2}{R^2}$$

Where ν is the Poisson's ratio for the material, E is the modulus of elasticity, h is the thickness, and R is the radius of the shell's mid-surface (a point between inner and outer radius). Due to the wide range of possible values for the Poisson's ratio and modulus of elasticity, averages were used from the MatWeb online material database. Note that although equation is used to represent elastic shells, assuming the hull of the submarine to be rigid should increase the pressure it can withstand and subsequently improve the depth that the submarine can survive at.

The depth that this pressure occurs at can be calculated from:

$$D = \frac{P}{\rho * g_e}$$

Where rho represents the density of the water. Calculations for the dome were done using SMATHStudio to reduce the likelihood of simple math errors when performed by hand. Units are automatically determined by the program, so mistakes are easy and quick to identify. Below (Figure 97) is an example of applying the program to the two equations above, with an example radius of 15.24 cm (6 inches), and a worst-case assumption for the thickness 0.15875 cm (1/16 inches).

```

E := 0.95 GPa Value from Mat Web can vary from 0.0420 - 3.30 GPa
v := 0.4 Value from Mat Web can vary from 0.370 - 0.430

h := 1/16 in Use the thinnest point on the dome, which is the apex.
Assuming the use of a dome from https://plastic-domes-spheres.com/plastic-domes

R := 6 in

beta := sqrt(3 * (1 - v^2))

Pdif := (2 * E) / beta * h^2 / R^2 = 18.8361 psi This excludes the air pressure above the water, which is assumed to equal the air pressure in the submarine.

Convert to depth rho is water density ge is gravity acceleration

rho := 1.02 g/cm^3 Valid for sea-water, yielding slightly less depth (Use 1.0 for fresh). Pressure varies less than 1% over range of 40F to 100F

Depth := Pdif / (rho * g_e) = 42.5966 ft

```

Figure 97: Sample calculations for dome thickness (Created by the Authors)

Note that the density for seawater is used for the example calculation, and that it is different from that of fresh water. The density of the water depends on the concentration of salt dissolved in the water, with both 1.02 g/cm³ and 1.03 g/cm³ able to be used as the density value. The value of 1.025 g/cm³ will be used for future calculations as this is an average.

A similar process was performed for the thickness of the submarine hull, but for the buckling pressure of a perfectly circular cylinder. Assumptions are made based on the “David Taylor Model Basin” formula provided by Windenburg and Trilling [12, equation 2]. The pressure calculated should be equal if not greater than the pressure and depth found for the dome using equations like in Figure 98. Supporting ribs must also be added, to support possible weaker sections if 3D printing is used. An example calculation is shown below.

P_{cr} = buckling pressure`

$t := 0.125 \text{ in}$ Wall thickness of circular cylinder

$L := 2 \text{ in}$ Unsupported length of cylinder i.e, distance between ribs

$a := 8 \text{ in}$ Mean radius of circular cylindrical shell

$E := 2.7 \text{ GPa}$ Young's (or tensile) modulus

$\nu := 0.36$ Poisson's ratio

$$P_{cr} := \frac{\left(2.42 \cdot E \cdot \left(\frac{t}{2 \cdot a} \right)^{\frac{5}{2}} \right)}{\left(1 - \nu^2 \right)^{\frac{3}{4}} \cdot \left(\left(\frac{L}{2 \cdot a} \right) - 0.447 \cdot \left(\frac{t}{2 \cdot a} \right)^{\frac{1}{2}} \right)} = 66.3634 \text{ psi}$$

The goal is to exceed the pressure of the the hemispheric dome under about 43 feet of water, or 19 psi

Figure 98: Sample calculations for hull thickness (Created by the Authors)

9.2. Housing

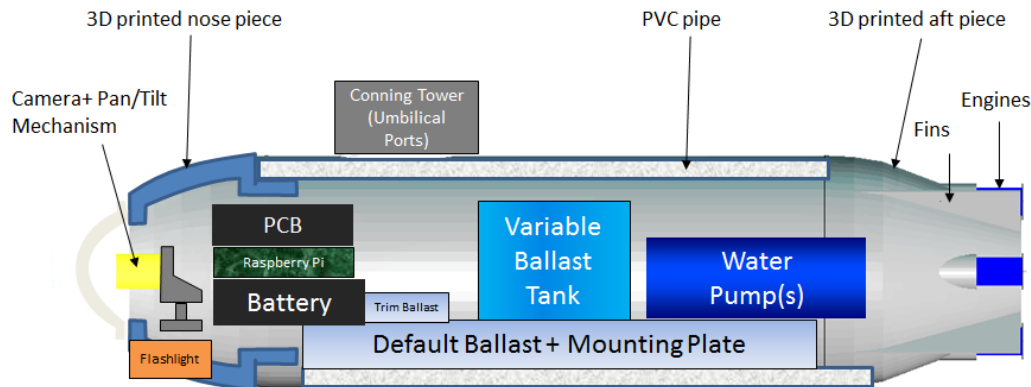


Figure 99: Possible submarine layout (Created by the authors)

In examining materials to design the submarine, making intricate shapes like those shown above in Figure 99 and emulating the 2D sketch shown in Figure 3 made 3D printed materials like PLA an obvious choice. As can be seen, the equations in Section 9.1 can be used to ensure that the entirety of the submarine can withstand the pressure at its placed depth. This is because the submarine in this design can be approximated as a combination of a sphere with cylinders and truncated cones. A 3D rendering of the design is shown below in Figure 100.

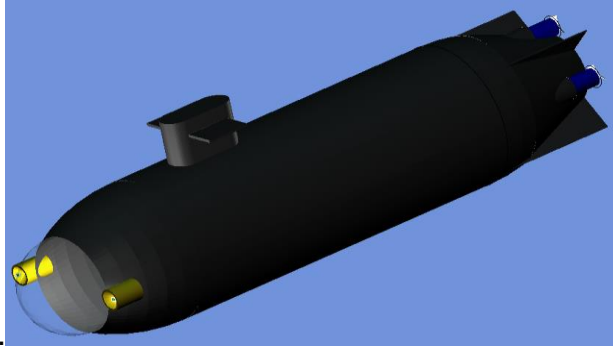


Figure 100: 3D Rendering of the submarine (Created by the authors)

As discussed above, acrylic has been considered for the clear dome due to its common use in aquatic applications. As for the rest of the body, we had also previously considered 3D printing to be able to make the complex shapes seen in the image above. One kind of plastic we considered using was PLA, which is a common plastic used for printing as well as being biodegradable. However, we found that 3D printing was too expensive, no matter the material. The more complex shapes such as near the front and aft of the submarine will be 3D printed, whilst the body will be a thick PVC pipe to be cost-efficient. Picking an appropriate schedule number will be based on the calculations made in Section 9.1. The more complex shapes though will be 3D printed, such as the truncated cones. An example pressure calculation is shown in Figure 101.

$$\begin{aligned}
 E &:= 2.7 \text{ GPa} \\
 \nu &:= 0.75 \\
 r_1 &:= 4 \text{ in} \quad \text{radius of small end of cone} \\
 r_2 &:= 8 \text{ in} \quad \text{radius of large end of cone} \\
 L &:= \sqrt{32} \text{ in} \quad \text{slant length of cone} \\
 \alpha &:= 30 \text{ deg} \quad \text{semivertex angle of cone} \\
 t &:= 0.1875 \text{ in} \quad \text{wall thickness} \\
 \rho_{bar} &:= \frac{r_1 + r_2}{2 \cdot \cos(\alpha)} = 0.176 \text{ m} \quad \text{average radius of curvature of cone} \\
 P_{cr} &:= \frac{0.92 \cdot E \cdot \nu}{\left(\frac{L}{\rho_{bar}}\right) \cdot \left(\frac{\rho_{bar}}{t}\right)^2} = 39.8741 \text{ psi}
 \end{aligned}$$

Figure 101: Sample calculations for truncated cones (Created by the Authors)

9.2.1. After Demo Hull Update

The ogive, conning tower, and rear truncated cone were ultimately printed from PLA at 20% infill. It is very likely that the pressure resistance overall was compromised as a result, but at a depth of 8 feet – the depth of Avery's pool - the submarine hull survived. All in all, it took about 10 days to manufacture all of the parts at a print speed of 60 mm/s.

10. Administrative Chapter

In terms of a budget plan the goal is to maintain a cheaper alternative to the other underwater submarines currently on the market. With this in mind, the range of prices you often see on the market is between \$1,000 and \$2,600. On the lower end of the market the pricing gives you a simple drown with either no camera or a still camera that has a limited camera feed. On the high-end you have an extremely expensive product that has the same capabilities as something that could be much cheaper. The other Administrative goal of this project is to plan and properly execute a project in a team environment and make appropriate deadlines of the semester.

10.1. Estimated Project Budget and Financing

We estimate our project with all its equipment and the resources needed to total around \$1000, or around \$250 per group member. Our estimated budget is shown below in Table 21, which has been modified to include our latest research into costs.

Table 21: Budget

Budget (Part 1)	
Item	Estimated Amount
Camera	\$150
Pan/Tilt Mechanism	\$50
Camera waterproofing case	\$35
Metal shielding for cable (50 ft)	\$30
Waterproof cable (50 ft)	\$50
3d printer materials	\$100
Pressurization materials for hull	\$50

Budget (Part 2)	
Air compressor	\$0 (use Madison's)
Raspberry Pi (x2)	\$150
4-inch display	\$40
2 axis joystick (x3)	\$25
Push button (x4)	\$25
Rotary Encoder	\$5
Battery	\$30
Propellers	\$30
Other	\$230
Total	\$1000

10.2. Per Item Budget Comparison

Prior to the midterm demo, we wanted a general idea of how much everything cost and if we were keeping under the \$1000 budget. As can be seen from the following subsections, these were our initial projections and thoughts regarding these items. The land battery and sheathing of course does not reflect the reality of the end product, and should be thought of as developmental milestones rather than true ones.

10.2.1. Camera

With the Camera there were multiple alternatives in terms of both prices and qualities. Originally, we planned to use a Go Pro Hero 7 which would give the immediate capability of recording and live streaming to the Raspberry Pi in 4k definition however the cost of the camera would go over the budgeted value. We saw the over budget not as an issue due to the camera's environment resistant

capabilities and the quality of image it could produce but once compared to the Raspberry Pi camera the quality was not good enough to outweigh the price.

Item	Cost	Difference from budget
Raspberry Camera Module V2	\$25	\$175 Gain
Go-Pro Hero 7	\$250	\$50 Loss
DEPSTECH 2K Office Webcam	\$35	\$165 gain
Sony IMX477	\$40	\$160 gain
Adafruit NTSC Serial Video Camera	\$40	\$160 gain
ELP-USB Camera Module	\$46	\$154 gain

Table 22 Camera Cost Comparison

Since we did not go with the Go Pro camera, we did not need to have a waterproofing case, so that money can go back into the main budget for something else.

The other alternatives seen in Table 22 are the Depstech webcam and the Adafruit NTSC, these cameras compared in price however they did not match the net gain of 175 by using the Raspberry camera. The size the size and performance of the Pi camera simply made its value more than rest of the options making it a better choice.

Another Particular Item that was reviewed heavily was the Raspberry Pi boards for both the controller and the submarine. Seeing Table 23 you can note that the Raspberry Pi 4 was not the most budget efficient item compared to competitors but also was not the worst of similar products that could have been used. The microcomputer was selected with the idea that there would have to be 2 of the same kind for the interfacing between the two devices to go smoothly. The closest to the duo Raspberry Pi 4 was the Asus tinker board which went over the budgeted value.

After the micro-computer and the Camera where decided the next item that was budgeted and compared was the Battery for supplying power to the submarine and to the controller separately. The larger battery needed to supply an ample amount of current and have enough voltage for the power over Ethernet process to work as intended.

Table 23 Micro Computer Budget Comparison

Item	Cost	Total Cost	Difference from budget
Raspberry Pi 4 Model B	\$55 x 2	\$110	\$40 Gain
Raspberry Pi 3	\$37 x 2	\$74	\$76 Gain
STM32MP157A-DK1	\$72 x 2	\$144	\$6 gain
Asus Tinker Board S	\$100 x 2	\$200	\$50 Loss
Rock Pi N10	\$99 x 2	\$198	\$48 Loss
Orange Pi 4B	\$67 x 2	\$134	\$16 gain

10.2.2. Sheathing for Cable

Clearly, as shown below in Table 24, the best choice for our budget is to get the nylon braided type of cable shielding. The two other types listed were nowhere near being in our budget. If we were to split the umbilical in two, the price would remain the same, meaning price is not dependent on configuration.

Type/Material	Price/ft	Total Cost	Difference from budget
Nylon Braided	\$0.32	\$32.00	+\$2.00
TechFlex Stainless Steel	\$2.37	\$237.00	+\$207.00
Reflex Braided	\$1.97	\$197.00	\$167.00

Table 24: Metal Shielding Choice

10.2.3. Waterproof Cable

We had to choose between the regular Ethernet cable or the 802.3bt Ethernet cable, which can supply more power to the submarine. Although the Ethernet cable that supplies more power is more expensive, shown in Table 25, the team needs this particular type of cabling to get the jobs done which are critical to the mission of the submarine. The Cat6 Ethernet cable with 802.3bt standard can supply over double what the regular Ethernet cable can provide.

Type/Material	Price/ft	Total Cost	Difference from budget
100 ft 802.3bt	\$0.35	\$35.00	-\$15.00
100 ft 802.3at	\$0.07	\$7.06	-\$42.94

Table 25: Waterproof Cabling Choice

10.2.4. Battery

For the main battery alone, the SigmasTek battery is close to that budget, and just barely exceeds it. However, the other options are way out of range. Although they all had nice features, sometimes the budget makes the calls, so there has to be some compromise in functionality. This battery that was chosen is the best battery for the job that also fits within the allotted price range shown in Table 26.

Table 26: Main Battery Choice

Battery Brand	Price/unit	Total Cost	Difference from budget
SigmasTek	\$8	\$40.00	+\$10.00
Makita 18V	\$60	\$180	+\$150.00
VISET Ebike	\$170	\$170	+\$140

The propeller batteries were not taken into account in the beginning. In the beginning, we thought we were going to be able to power everything from one battery. When the power budget got a little out of control, we had to think about adding extra batteries. This extra cost is a little out of the budget, but our project has to work, and it must have power to work, so this is not a cost that we cannot forego. These prices were then compared to the budget shown in Table 27.

Table 27: Propeller Battery Choice

Battery Brand	Price/unit	Total Cost	Difference from budget
Youme Power Pack	\$28.50	\$114.00	+\$114.00
SafeAMP 12	\$40.00	\$40.00	+\$40.00

10.3. General Project Milestones

Milestone	Date/semester
Choose Propulsion method & devices	March 1st
Design PCB	March 10th
Choose Pressurization method and devices	March 15th
Design Software controls and Video	March 20th
Design Hulls for submarine	March 31st
Create submarine Hulls and Test watertightness	End of Semester
Print PCB Layout and board	End of semester
Assembly of winch system	Beginning of Senior Design 2
Assemble Submarine	Beginning of Senior Design 2
Final testing and troubleshooting	Middle of Senior Design 2
Have submarine fully functional	End of Senior Design 2

Table 28: Early Forecasting of Milestones

Table 28 contains our project milestones for both semesters of Senior Design. We also provide milestones of different elements of our design in Table 29 and Table 30 below. Note that completion of the submarine hull itself is determined by when the pressurization measurements are complete. Getting completion of these coordinated is difficult due to how closely linked the physical requirements of the submarine are to each other. For example, the hull size is determined by the size of the internal components; the engines are an internal component, and depend on how heavy the submarine is; the buoyancy system also depends on how big the submarine is; with similar problems continuing throughout design.

10.4. Tech Milestones (Computer and Submarine Body)

Table 29 below focuses on the milestones for the computer and hull of the submarine. It is expected that coding and hull design will be finished early in the beginning of Senior Design II to allow for ample time to test and debug the systems of the submarine. We also expect the 3d printed parts to be quick to print, and as such, have allocated only fourteen days to both design and print them. This task in particular can be arduous though, as part tolerances and adjustments must be included on a case by case basis and won't be able to be universally applied.

Table 29: Early, optimistic, milestone forecasting for the submarine controller and submarine body

Milestone	Expected Completion
<i>On-Board Computer</i>	
Tech Investigation Completion	02/24/21
Designing the 3D model	03/04/21
Printing the 3D model	03/24/21
Start of ordering Parts	03/24/21
Fitting parts	04/07/21
Wiring the parts	04/07/21
Coding the commands	04/21/21
Debugging with software	04/28/21
Test with software	05/05/21
Attach to Submarine	05/05/21
Debug with Submarine	05/12/21
First test run in water	05/12/21
Refine in water	06/16/21
Demonstrate final product	07/21/21
<i>Submarine Body</i>	
Design Investigation	02/24/21
Design 3D model	03/10/21
Printing the 3D parts, Start of ordering Parts	03/24/21
Inclusion of Raspberry Pi and Coding efforts	04/21/21
Testing	05/12/21

10.5. Tech Milestones (Pressure Control and Propulsion)

Tech Milestones	
Milestone	Expected Completion
<i>Pressure Control</i>	
Tech Investigation Completion	02/24/21
Design Investigation Completion	03/03/21
Pressure Tests	03/03/21
Parts Ordered	03/10/21
Pressure Control Design and Prototyping	04/07/21
Submersion Testing	05/12/21
<i>Propulsion</i>	
Tech Investigation Completion	02/24/21
Design Investigation Completion	03/03/21
Parts Ordered	03/05/21
Engine Control Wiring	03/17/21
Vectoring Testing	04/14/21

Table 30: Early milestone forecasting for the pressure control and propulsion systems.

Note that some of the items in the above tables have been completed, however, due to the tables representing early milestone forecasting, this cannot otherwise be represented (in a visually satisfactory manner) until more items have been completed. This is because the table would then be a mix and would be less effective in communicating the timeline. Some items were also completed out of order and would contribute to this reduced effectiveness. A more updated set of tables will be provided for Senior Design II.

10.6. After Demo Administrative Update

Many of the date goals listed above weren't reached. This is not surprising, as these dates were chosen at the start of the project. Likewise, the budget was drastically overshot, and while we are in the similar price range of other competitive submarines, we still were unsuccessful with our monetary goal. Figure 102, Figure 103, Figure 104 show the project timeline (in days spent) and total budget respectively.

Project Timeline

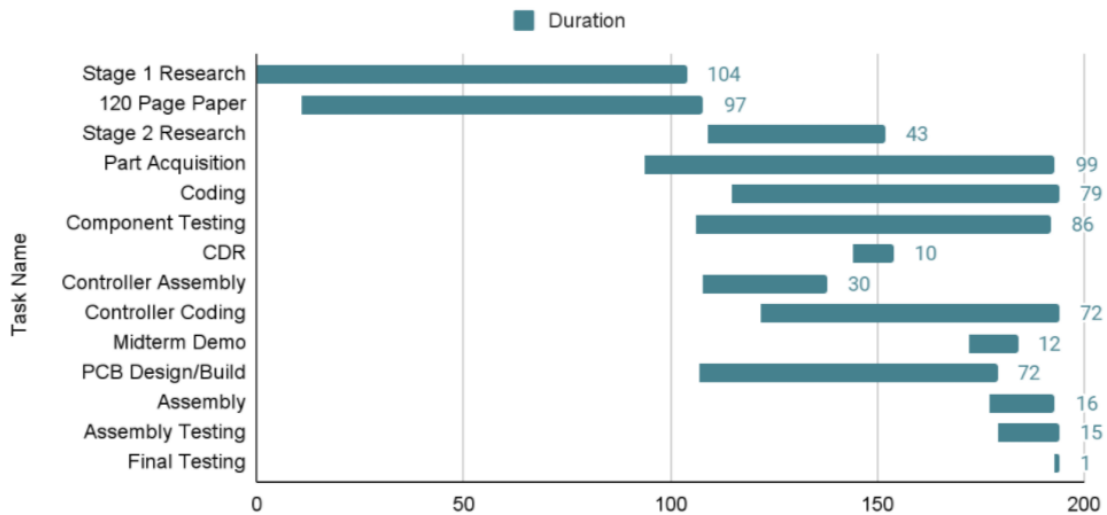


Figure 102: Project Timeline (Created by the Authors)

As can be seen from the timeline, quite a bit of time was spent doing Stage 2 research. This research included the buoyancy calculations and other minor research not performed in Senior Design I. Note also how many of the above processes completed shortly before final testing. This was because many of the systems could not be put together and properly tested until all parts were in the same location and attached to the submarine Pi.

Total Budget Chart (pt. 1)

Submarine Components					
Item	Purpose	Weight/Item	Price/Item	Price Allotted	Price for Parts
Controller				\$250.00	
Controller + Parts	controller	17.24 ounces	NA		\$86.64
Raspberry Pi	controller	1.76 ounces	\$75.00		\$75.00
Total spent :\$161.64 Budget left:\$88.36					
PCB				\$250.00	
Batteries*	Motors,Pi's,Sub	82.89 ounces	\$120.00, \$180.00		\$300.00
Ethernet Cable	Transfer Power/Info	N/A	\$35.00		\$35.00
PCB + parts	Controls power flow	10.58 ounces	N/A		\$561.47
Motors	Propulsion	2.64 ounces	\$25		\$50.00
Battery Charger**	Charge Batteries	25.57 ounces	\$20.00		\$20.00
Total spent :\$966.47 Budget lost:\$-716.47 After controller budget gain there is \$-628.11					

*Includes land battery, **Part of support equipment

Figure 103: Budget Part 1 (Created by the Authors)

Submarine Components					
Item	Purpose	Weight/Item	Price/Item	Price Allotted	Price for Parts
Ballast				\$250.00	
Baylite pump	Inflow pump	10.56 ounces	\$26.50		\$26.50
Irontron 12v pump	Exflow pump	28 ounces	\$52.99		\$52.99
11.1V 5.2A/h Battery	Exfil Pump Power Supply	12.66 ounces	\$65.69		\$65.69
Bladder	Bladder	6 - 70 ounces	\$12.99		\$12.99
Total spent :\$158.17	Budget left:\$91.83	After controller+PCB budget gain there is -\$536.28			
Submarine				\$250.00	
Sub shell Parts	Contain Parts	50.74 ounces	\$29.31, \$30.00		\$59.31
Camera + PI	Send live feed	1.41 ounces	\$75.00, \$29.95		\$84.95
Pan tilt mechanism	Allows for camera movement	1.05 ounces	\$6.95		\$6.95
			\$1.00, \$72.00,		
Extra sensors	Monitor distance	1.76 ounces	\$15.00		\$88.00
Acrylic Dome	Viewing dome	5.29 ounces	\$34.50		\$34.50
Rebar	Counter Weight	83.44 ounces	7.38		\$126.35
Total spent :\$400.06	Budget left:\$-150.06	After controller+PCB+Ballast budget gain there is -\$686.35			Total spent: \$1686.35

Figure 104: Budget Part 2 (Created by the Authors)

The budget outline above shows how far we missed our budget goal. The most unexpected high price items were the PCBs and the rebar, as the PCBs were anticipated to be much cheaper and the rebars were a surprise purchase due to the mistake mentioned earlier in the paper.

10.6.1. Additional Diagrams

Figure 105 and Table 31 show the final work distribution amongst the team.

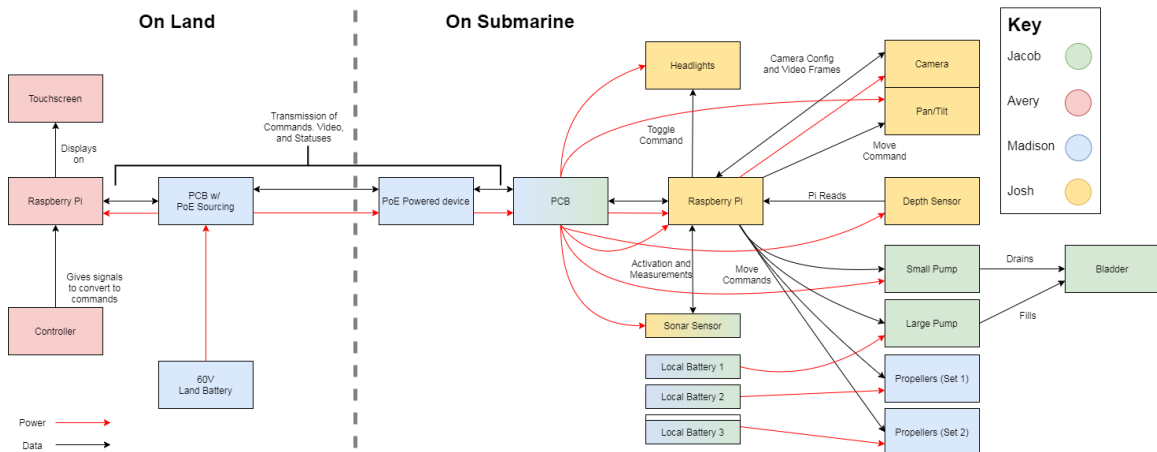


Figure 105: Final Work Layout (Created by the Authors)

Engineer	Responsibility
Jacob	Movement, Cabling, Power, Ballast
Madison	Movement, Cabling, Power, PoE
Avery	Command/Control
Joshua	Vision, Hull, Final Assembly

Table 31: Engineering Responsibilities

11. Conclusion

This project began solely as the idea to have a remotely controlled underwater camera. It was raw but came straight from the desire to want such a product. The full extent of its capabilities was not yet known, and the idea was nebulous within the minds of all team members. The idea then manifested into a remotely operated submarine that can be used for exploration and fun, a device able to be used by people of all ages and abilities.

While a submarine tethered to a hand-held controller with a video screen was always a requirement, other important features were determined as the semester progressed. The use of this video necessitated rapid transmission of video, which could be accomplished using multiple Raspberry Pis and to transmit between them using their Gigabit Ethernet capabilities. The next feature to be added was the ability to reel in the submarine with the hand crank, along with the goal to have several ways to determine the power level of the submarine. Following that was a variable headlight, a feature deemed necessary after examining other products in the market. A fixed brightness headlight was deemed too detrimental to exploration as the user could not adjust the light based on their surroundings.

Surprisingly, the most important feature to this submarine – the rotatable camera – was not fully discussed until halfway through the semester. This was because initial research had proved misleading and disheartening. At first, it seemed that most pan/tilt mechanisms would be quite expensive, and those that were within our budget did not have the necessary support. Even community support for products seemed to be thin, and reliant on disassembling the device and risking damage. It was not until an affordable pan/tilt mechanism was found could the camera for the submarine be upgraded from a static camera to a rotatable one. Not only could the camera be rotated from side to side, but also up and down, making aquatic exploration much more enjoyable, and allowing users to better track the underwater action.

All the features described so far have been supported by our research into the ideas, key technologies, and components needed to make them happen. They have also been supported by our budget of \$1000, which is a key point in our design. Our product will come with the sensors and standard features expected of a typical remote-controlled submarine, and our design will ideally provide an improved user interface and experience.

This project will give us experience with software communication and embedded design. Having completed the rapid development and testing of the prototype for Senior Design II, we find ourselves ready to enter the larger engineering world.

To see the videos for the final presentation and demonstration along with the conference paper, please visit:

<http://maverick.eecs.ucf.edu/seniordesign/sp2021su2021/q19>

12. Copyright Page

In terms of the part selection section, the images used are only temporary and will be replaced with actual products once they have been received. Emails asking for approval will also be sent in order to gain permission anyways. Although the yellow fish used in the Senior Design I version of this document is not present, we have kept the notice for its usage below.

Item 11: Yellow Cliparts

“Looking for the best yellow cliparts? Search no more! We have 52 free yellow clip arts for you. Feel free to use them in your documents, websites, or presentations. You can also share a yellow clipart in social media sites or apps from our site.”

13. References

- [1] "Power over Ethernet - Everything You Need to Know." Intellinet Europe, intellinetnetwork.eu/pages/power-over-Ethernet. Accessed 1 May 2021.
- [2] "Power over Ethernet." Wikipedia, 5 Feb. 2021, https://en.wikipedia.org/wiki/Power_over_Ethernet.
- [3] "Researchers Create Fiber Network That Operates at 99.7% Speed of Light, Smashes Speed and Latency Records - ExtremeTech." ExtremeTech, 25 Mar. 2013, www.extremetech.com/computing/151498-researchers-create-fiber-network-that-operates-at-99-7-speed-of-light-smashes-speed-and-latency-records.
- [4] RealPars. "What Is Ethernet?" YouTube, 14 Jan. 2019, <https://www.youtube.com/watch?v=HLziLmaYsO0>.
- [5] "Flexo Stainless Steel Expandable 1/2" - WireCare.com." Wwww.wirecare.com, www.wirecare.com/category/braided-sleeving/metal-shielding-sleeving/flexo-stainless-steel-xc/ssl0-50sv-flexo-stainless-steel-xc-1-2-silver-5-ft-cuts. Accessed 1 May 2021
- [6] <https://www.electriduct.com/Nylon-Multifilament-Braided-Sleeving.html>
- [7] Evkin, Alexander, et al. "Buckling of a Spherical Shell under External Pressure and Inward Concentrated Load: Asymptotic Solution." Mathematics and Mechanics of Solids, vol. 22, no. 6, 21 Mar. 2016, pp. 1425–1437, <https://eprints.keele.ac.uk/1563/1/Stability.pdf>, 10.1177/1081286516635872. Accessed 1 May 2021.
- [8] http://www.matweb.com/search/datasheet_print.aspx?matquid=632572aeef2a4224b5ac8fbd4f1b6f77
- [9] Plastic Domes | Plastic Hemispheres | California Quality Plastics. <https://lastic-domes-spheres.com/plastic-domes>. Accessed 1 May 2021.
- [10] Sarikas, Christine. "What Is the Density of Water? By Temperature and Unit." Prepscholar.com, 2018, <https://blog.prepscholar.com/what-is-the-density-of-water>.
- [11] "Yellow Cliparts - Cliparts Zone." Cliparts.zone, <https://cliparts.zone/yellow-cliparts>. Accessed 1 May 2021.
- [12] Login – the Journal of Ocean Technology. https://www.thejot.net/login/?page_id=837&show_article_preview=84&jot_download_article=84). Accessed 1 May 2021.
- [13] Flynt, Joseph. "What Is PLA? Polylactic Acid Properties, Uses, & Melting Point - 3D Insider." 3D Insider, 10 Nov. 2017, <https://3dinsider.com/what-is-pla/>.
- [14] <https://www.professionalplastics.com/professionalplastics/MechanicalPropertiesofPlastics.pdf>
- [15] "Amazon.com VISET Ebike Battery Pack 36V 48V 10Ah 14Ah 20Ah Electric Bike Battery Li-ion with 2Ah Charger for 350W 450W 750W 500W 800W 1000W Electric Bicycle Motor." Wwww.amazon.com, https://www.amazon.com/VISET-Battery-Electric-Charger-200W-500W/dp/B08ND2916P/ref=asc_df_B08ND2916P/. Accessed 1 May 2021.

- [16] "Makita USA - Product Details -BL1850B." Makita USA, www.makitatools.com/products/details/BL1850B . Accessed 1 May 2021.
- [17] "12 Volt 5 Amp Sealed Lead Acid Battery." Replacement Battery Store, <https://replacementbatterystore.com/12V-5AH-SLA-Battery/?msclkid=40291092e2c714d5e81f701980143214> . Accessed 1 May 2021.
- [18] "Amazon.com: Lipo 4S Battery, 14.8v 3300mAh Lipo Battery Pack 50C with T Plug for RC Helicopter Airplane Submarine Quadcopter (2 Packs): Toys & Games." Wwww.amazon.com, <https://www.amazon.com/Youme-Power-Helicopter-Airplane-Quadcopter/dp/B07RYTMMN4> . Accessed 1 May 2021.
- [19] <https://www.sears.com/safeamp-replacement-battery-for-fisher-price-power-wheels/p-A020418679>
- [20] <https://www.rcelectricparts.com/40a-rc-brushless-motor-electric-speed-controller-esc-3a-ubec-with-xt60--35mm-bullet-plugs.html>
- [21] "Amazon.com: Opaltool Brushless Controller, 36V/48V Aluminium Alloy E-Bike Brushless Motor Controller for Electric Bicycle Scooter." Wwww.amazon.com, https://www.amazon.com/Opaltool-Brushless-Controller-Aluminium-Electric/dp/B07XMJC8S2/ref=asc_df_B07XMJC8S2/. Accessed 1 May 2021.
- [22] "Reflex Reflective Sleeving | Special Braided Sleeving." Electriduct, <https://www.electriduct.com/Reflex-Reflective-Sleeving.html> . Accessed 1 May 2021.
- [23] <https://www.amazon.com/BESTSUN-Flashlight-Waterproof-Portable-Headlamp/dp/B00P8N4ASW/>
- [24] "Amazon.com: Liuqingwind 12-24V 20A Brushless Motor 4 Blade Underwater Thruster RC Bait Submarine Accessory Toys Gifts Clockwise: Toys & Games." Wwww.amazon.com. Accessed 1 May 2021.
- [25] "60 ML Syringe with Luer Lock Sterile EO (5 Pcs / Box)." Liliium Laboratory Equipment and Supplies Inc., <https://www.llesinc.com/product/60-ml-syringe-with-luer-lock-sterile-eo-5-pcs-box/> . Accessed 1 May 2021.
- [26] "Reusable 100ml-200ml Big Large Hydroponics Nutrient Measuring Syringe Tools for Sale Online." EBay, <https://www.ebay.com/p/8030326813> . Accessed 1 May 2021.
- [27] "Building and Testing a Lego-Powered Submarine." Wwww.youtube.com, <https://www.youtube.com/watch?v=tGEZApd9MMk> . Accessed 1 May 2021.
- [28] "Amazon.com : HEEPDD 5V USB DC Submersible Water Pump, Brushless Aquarium Fish Tank Fountain Water Pump Waterproof Pet Fountains : Pet Supplies." Wwww.amazon.com, <https://www.amazon.com/HEEPDD-Submersible-Brushless-Waterproof-Fountains/dp/B07T6GDNT3>.
- [29] "Amazon.com : PULACO 95GPH 5W Mini Submersible Water Pump for Aquarium Fish Tank, Pond, Fountain, Hydroponics : Pet Supplies." Wwww.amazon.com, <https://www.amazon.com/PULACO-Submersible-Aquarium-Fountain-Hydroponics/dp/B07SLKDW5J> .

- [30] “Amazon.com: LICHIFIT RC Jet Submarine Underwater Motor Thruster 7.4V 16800RPM CW CCW 3-Blades Propeller for DIY Micro ROV Robot RC Bait Submarine Submarine Accessories: Toys & Games.” Wwww.amazon.com, <https://www.amazon.com/LICHIFIT-Underwater-Propeller-Submarine-Accessories/dp/B07WY4MDYZ> .
- [31] “48 Tools BH-MAK-BLU-04 Makita 18V 4-Unit Battery Holder.” Atlas-Machinery, www.atlas-machinery.com/48-tools/bh-mak-blu-04/ .
- [32] “Amazon.com: Hygger Ultra Quiet 53GPH (200L/H, 3W) Submersible Mini Water Pump Comes with 2 Nozzles, for Aquariums, Fish Tank, Fountain, Hydroponics, Max Lift Height 1.7ft ,120V/60HZ, Power Cord 6ft: Home Improvement.” Wwww.amazon.com, <https://www.amazon.com/Submersible-Nozzles-Aquariums-Fountain-Hydroponics/dp/B07ZNPZWMR> .
- [33] “Amazon.com: Winkeyes DC 12V Submersible Fountain Pump with 118" High Lift, 3.6W Mini Electric Brushless Fountain Water Pumps.” Amazon.com, 2021, https://www.amazon.com/Winkeyes-Submersible-Fountain-Electric-Brushless/dp/B07S8S8JR9/ref=asc_df_B07S8S8JR9/. Accessed 1 May 2021.
- [34] “Amazon.com: HiLetgo 20pcs TCT40-16R/T 16mm Split Ultrasonic Sensor Ultrasonic Transceiver Probe 10 Transmitters + 10 Receivers T+R Ultrasonic Sensor Set: Office Products.” Amazon.com, 2021, <https://www.amazon.com/HiLetgo-Ultrasonic-Sensor-Transceiver-Receiver/dp/B00M2GHG66> . Accessed 1 May 2021.
- [35] “Amazon.com: HiLetgo 4pcs Ultrasonic Sensor Integrated Transceiver Waterproof Diameter 16MM: Office Products.” Amazon.com, 2021, <https://www.amazon.com/HiLetgo-Ultrasonic-Integrated-Transceiver-Waterproof/dp/B00M2GH954> . Accessed 1 May 2021
- [36] <https://www.digikey.com/en/products/detail/dfrobot/SEN0208/6588472?s=N4lgTCBcDaIMoFEBYAGMKACiC6BfIA>
- [37] “Amazon.com: SainSmart HC-SR04 Ranging Detector Mod Distance Sensor (Blue).” Amazon.com, 2021, www.amazon.com/SainSmart-HC-SR04-Ranging-Detector-Distance/dp/B004U8TOE6 . Accessed 1 May 2021.
- [38] <https://www.newark.com/prowave/400sr160/ultrasonic-sensors/dp/98K9170>
- [39] Satoms. “RJ45 Pinout Wiring Diagram for Ethernet Cat 5, 6 and 7.” Satoms, 21 Dec. 2015, <https://satoms.com/Ethernet-cable-pinouts/>.
- [40] “MarineWeld Twin Tube.” J-B Weld, www.jbweld.com/product/marineweld-twin-tube. Accessed 1 May 2021.
- [41] https://www.amazon.com/eBoot-Plastic-Waterproof-Adjustable-3-5-13mm/dp/B01GJ03AUQ/ref=sr_1_2_sspa?dchild=1&keywords=waterproof+grommet+5+pack&qid=1619885502&sr=8-2-spons&psc=1&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUEzOFBKSIQwOThUOVFJJmVuY3J5cHRIZEikPUEwNjUzMTQ2MjVDT045S05NRTIRRSZlbnNyeXB0ZWRBZEikPUEwMjIxMDM4MkY2VjdENE9SSjNFQyZ3aWRnZXROYW1IPXNwX2F0ZiZhY3Rpb249Y2xpY2tSZWRpcmVjdCZkb05vdExvZ0NsaWNrPXRydWU=

- [42] "Phoenix Contact 1725656." Mouser Electronics, <https://www.mouser.com/ProductDetail/Phoenix-Contact/1725656>. Accessed 1 May 2021.
- [43] NASA SPACE VEHICLE DESIGN CRITERIA (STRUCTURES) BUCKLING OF THIN-WALLED TRUNCATED CONES. , 1968. <https://ntrs.nasa.gov/api/citations/19690014753/downloads/19690014753.pdf> Accessed, 1 May 2021
- [44] "Amazon.com: GeeekPi 5 Inch HDMI Monitor LCD Resistive Touch Screen 800x480 LCD Display USB Interface for Raspberry Pi 4 Model B, Pi 3/2 Model B/B+ & Banana Pi (Plug and Play Free Driver): Computers & Accessories." *www.amazon.com*, www.amazon.com/GeeekPi-Monitor-Resistive-Interface-Raspberry/dp/B01L6O2NEE. Accessed 1 May 2021.
- [45] https://www.digikey.com/en/products/detail/raspberry-pi/RASPBERRY%2520PI%25203%2520MODEL%2520B%2B/8571724?utm_adgroup=&utm_source=bing&utm_medium=cpc&utm_campaign=Shopping_DK%2BSupplier_Other&utm_term=&utm_content=&utm_id=bi_cmp-384720322_adg-1302921564539927_ad-81432658925801_pla-4585032212989118_dev-c_ext-prd-8571724&msclkid=c9fc3843b4c0163a723a58ce28549f11
- [46] Anker. "PowerCore Slim 10000." *Anker*, <https://us.anker.com/products/a1229>. Accessed 1 May 2021.
- [47] Industries, Adafruit. "2-Axis Joystick." *www.adafruit.com*, www.adafruit.com/product/245. Accessed 1 May 2021.
- [48] "Adafruit Push-Button Power Switch Breakout – Pimoroni." *Shop.pimoroni.com*, <https://shop.pimoroni.com/products/adafruit-push-button-power-switch-breakout>. Accessed 1 May 2021.
- [49] Industries, Adafruit. "Rotary Encoder + Extras." *Www.adafruit.com*, www.adafruit.com/product/377. Accessed 1 May 2021.
- [50] Foundation, The Raspberry Pi. "Raspberry Pi OS." Raspberry Pi, www.raspberrypi.org/software/.
- [51] "Plastic Extension Cords & Surge Protectors at Lowes.com." Lowe's, www.lowes.com/pl/Plastic--Extension-cords-surge-protectors-Electrical/4294542242?refinement=4294965728. Accessed 1 May 2021.
- [52] <https://www.analogictips.com/pulse-width-modulation-pwm/>
- [53] "Black Silicone Sealant & Adhesive." J-B Weld, <https://www.jbweld.com/product/black-silicone>. Accessed 1 May 2021.
- [54] <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3110782/#:~:text=Our%20results%20show%20that%20over,further%20than%2010%20km%20away.>
- [55] <https://science.nasa.gov/earth-science/oceanography/living-ocean#:~:text=There%20are%20about%20620%2C000%20kilometers,the%20Indian%20Ocean%20in%202004.>

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