# NC State University Technical Design Report

Marcus Behel
*Computer Engineering*

Nolan Canegallo
*Aerospace Engineering*

Justin Hodakowski
*Electrical & Computer Engineering*

Daniel Mitchum
*Computer Engineering*

Amr Moussa
*Computer Science*

Christopher Mori
*Electrical & Computer Engineering*

Samarth Patel
*Biomedical Engineering*

Tajah Trapier
*Materials Engineering*

***Abstract*—SeaWolf VIII (SW8) is a returning design from the 2021 RoboSub competition developed by the North Carolina State University Underwater Robotics Club. Building off of the results from RoboSub 2021, emphasis was placed on upgrading the electrical system and developing our software and acoustics systems. Initial efforts centered on ensuring the robot would be functional for pool testing and competition as well as implementing necessary changes to ensure electrical and mechanical stability. Once upgrades and new designs were implemented, the team shifted focus to developing our signal sensing peripherals, new cameras, computer vision code, hydrophones, and acoustics echo location code through pool testing. Significant time and work was also dedicated to ensuring the robot could move autonomously within a pool.**

## I. Competition Strategy

The Underwater Robotics Club at NC State continued development of the SeaWolf VIII platform for its first ever in-person competition. Our aim was to ensure that SeaWolf VIII became an entirely autonomous vehicle, capable of completing four tasks in the competition course. This goal carries over from last year's conservative approach to scoring as many points as we can in the following tasks:

1) Gate
2) Path
3) Buoys
4) Octagon

Focus was given to completing the base tasks, as opposed to targeting bonus and style points. While the team was confident that it could successfully approach each task listed, incorporating style points added another layer of complexity that the team was not confident it could achieve within the competition time frame.

Gate was the highest priority task as its completion is required to attempt the remaining obstacles in the course. Path and Buoys closely follow Gate, require vision and precede Octagon; so naturally, those were the next objectives. Octagon's prioritization over other obstacles in the remaining portion of the course was due to the fact that it holds high point value, our team has a dedicated acoustics sub-team, and other tasks require heavy mechanical development to achieve.

Completing these tasks necessitates a modular system equipped with a stable frame, an efficient and organized electrical system, and robust software for processing peripheral input and output. Consequently, improvements were made to the existing SeaWolf VIII platform to equip the system with such features.

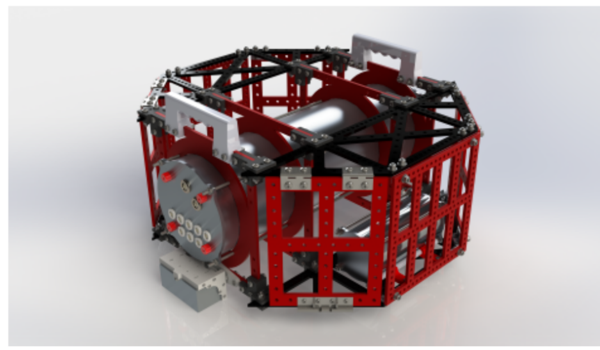

Fig. 1. SeaWolf VIII Render

Last year, the mechanical effort was focused on building a robust movement system and solid frame for development and testing. This year, the primary focus for the mechanical team was on reconfiguring the robot to accommodate the updated electrical system and additional peripherals. Additionally, the team worked to construct competition props to train software for our targeted vision tasks.

The original electrical design for SeaWolf VIII focused on developing a stable platform with mostly off-the-shelf components. This allowed the entire team to work on developing other parts of the robot to compete in competition.

This year, three strategic improvements were made to the electronics system. Firstly, our single source power system was converted into a load balancing system, allowing us to run two external batteries. This improvement provided SeaWolf VIII with a longer run-time and removed the danger of a LiPo battery from our main hull. Additionally, this decision freed-up space in the hull for future developments.

The second change to the electronics system stemmed from the first. Removing our large battery from the main hull called for the reorganization of electronics to support the configuration and control of the load balancing system. Mechanical was put into a support role for this, which included the creation of mounting solutions for internal components, reconfiguring the robot from one internal battery to two external batteries, and designing a new electronics-to-hull interface. The interface allows electrical connections to be made through both end caps of the main hull, and eliminates the need to manually plug in connections when sealing the end cap to the hull.

The third strategic improvement to the electrical system was to replace one of our custom electronics components with an off-the-shelf high-side switch. This component was not compatible with our replacement flight controller, which was swapped into the system due to an improved inertial measurement unit used for locomotion and depth-control.

The addition of external depth-cameras provided SeaWolf VIII with the ability to navigate the first of our three targeted competition tasks: Gate, Path, and Buoys. Each of these require visual processing to complete. As such, the critical path of the software team this year was developing robust code for computer vision, mission autonomy, and system behavior. A large amount of time and effort was spent creating high resolution physical simulations. These simulations allowed us to ensure software robustness, but at the cost of less development time on more complex software solutions.

To accomplish Octagon, this year's acoustics development saw the implementation of a new filtering circuit as well as the implementation of a time difference of arrival algorithm which approximates pinger location. PCB development was at the forefront to eliminate issues with hand built circuits, and to ensure a compact system that could be integrated into the main hull. To allow for parallel testing and development of the Acoustics system, a secondary platform was created which solely provided the Acoustics system with a robust, waterproof container and a connection to the surface such that pinger data can be collected at pool tests.

## II. Design Creativity

In the division of work amongst the team, four main subteams exist to work in parallel with one another. The mechanical team handles the robot's structure and hull, connection and mounting of peripherals, and construction of props for competition practice. The electrical team handles the power system of the robot as well as electrical control of the robot's locomotion. The software team handles mission code, how the robot responds to changes in motion, and the computer vision system. The acoustics team develops the listening system onboard the robot as it relates to signal receiving on hardware and processing in software.

### A. Mechanical

In the mechanical team, a design methodology of modularity and manufacturability is followed. In order to adhere to this methodology, creative solutions were needed for several components of SeaWolf VIII. There are four main areas where we implemented creative solutions.

One creative solution was the transition from a single battery in the main hull to two in external hulls. This solution presented the challenges of affecting buoyancy and creating drag if mounted above or below the frame of SeaWolf VIII. This was accomplished by using a similar setup of threaded rods to hold two end caps on a cylindrical hull and using 3D printed spacers and mount points for an adjustable mounting solution, as seen in figure 4 in Appendix A. Furthermore, to utilize the interior bays of SeaWolf VIII more efficiently, the vertical thrusters were moved to the outside of the frame (also reducing drag) and locking hinges were used to create doors on the two exterior bays. A detailed depiction of this design can be seen in figure 5 in Appendix A.

Another creative solution involved the interface between the rear end cap and the internal electronics. Since we cannot effectively unseal both end caps simultaneously, a quickly-disconnecting solution was required. To accomplish this, a series of keyed 3D prints were used in tandem with blank penetrators, ¼"-20 hardware, and power poles. This "Endcap Interface" is highly modular, self-aligning, and provides guaranteed electrical contact through carefully designed geometry. A detailed depiction of this design and its components can be seen in figure 6 in Appendix A.

An additional creative solution was our camera enclosures and mounts. The enclosure was machined from aluminum and assembled using a face gasket, acrylic front plate, 3D printed back plate for the camera and compressible spacers to minimize optical distortions. Tabs were also machined out to interface with our 3D printed modular mounting solution which can be attached in many different orientations and locations using pins and our standard hardware. A more detailed depiction of this solution can be seen in figures 7 and 8 in Appendix A.

The final solution we will discuss was the unforeseen reevaluation of SeaWolf VIII's hull material. Our hull was originally made from cast acrylic and experienced a crack, thus causing us to reevaluate this decision. To complete this decision a Pugh Matrix was used weighing various material properties and convenience features of polycarbonate, acrylic, and aluminum to determine their rankings. As a result of this process, it was decided to transition the hulls to aluminum. The decision process and Pugh Matrix are described in more detail within Appendix B. These changes did necessitate other changes such as using leak detection tape and leak sensors to account for the lack of optical clarity and transparency.

### B. Electrical

While many portions of the electrical system are built around off-the-shelf components, the challenges of operating SeaWolf VIII necessitate some custom solutions. Most of these custom solutions revolve around power distribution and system control.

Due to the high current requirements of running many thrusters, we found that the battery life of SeaWolf VII when using a single LiPo battery was less than ideal. Additionally, the battery took up a significant amount of space in the main electronics hull. Ultimately, the solution for both of these problems became the Load Balancing Board (LBB). The LBB is a custom PCB to allow the use of two 10Ah LiPo batteries in "parallel". This system distributes current load proportionally across the two batteries to ensure both are drained at the same rate, which avoids safety hazards related to mis-operating LiPo batteries. The board itself is relatively simple and consists of circuitry to drive the gate of two MOSFETs which distributes the load between the two batteries.

Using two batteries in parallel clearly improves battery life, but this specific solution was chosen as it also allowed space to be freed up in the main electronics hull by allowing the batteries to be moved out into separate hulls. This would not be possible with a single battery due to the system's current requirements. With two batteries, both be used as current sources. This distributes current between two wetmate connectors instead of just one to avoid generating too much heat and exceeding the current capacity of the wetmate connectors used. A detailed depiction of this design and its components can be seen in figure 9 in Appendix A.

The Main Electronics Board (MEB) is another custom designed portion of the system. The MEB is a PCB designed to sit on of a MSP430 development board. It is responsible for controlling system power and serves as a communication pathway between the Jetson and all other components of the electrical system (including most sensors). The choice to use an existing development board instead of integrating a microcontroller onto the MEB was motivated by the desire to reduce board complexity and failure points in the system. Two key functions of MEB are to control the thruster kill / arm status and to control system power. The system is powered by enabling the system power SSR. This is done by a button on MEB or a switch outside the robot that is connected to MEB. Once on, MEB will hold the system on using a output pin of the microcontroller. This allows a way for MEB firmware to shutoff the system if needed (eg in the scenario a leak is detected. Additionally, the same switch used to turn the system on can manually shutoff the system (not depending on MEB firmware) to ensure it is always possible to power off the system. The MEB is also responsible for arming the thrusters. SeaWolf VIII requires two conditions to arm the thrusters. First, the hardware killswitch must be in the "armed" position. Second, the robot software running on the Jetson must arm the system by pulling a GPIO pin high. This requires two components be in the path to ground the thruster SSR's coil enabling the SSR. First is the killswitch itself. The second is a MOSFET controlled by a Jetson GPIO. These two components are in series ensuring that even if the MOSFET fails, the thrusters are not armed unless the killswitch is closed. In addition to these core pieces of functionality, the MEB has additonal sensors integrated into it to facilitate the transition to the aluminum hull. Having a non-transparent hull made LED indicators and additional failure sensors critical parts of the system. As such a temperature / humidity sensor, leak sensor, and LED driver were added to MEB. Currently (due to man hours) these extra components have been added on an additional breadboard, but work on a new revision of MEB containing these components is underway and is planned to be completed before competition. A detailed depiction of this design and its components can be seen in figure 10 in Appendix A.

Last year we had an opto-isolator board used to disconnect the thruster ground from the system ground. This was removed because it was generating a falling edge delay on our PWM signals from the cube Orange. We realized that it would be much simpler and safer to high side switch both the system and thrusters instead of high side and low side switching them respectively.

Initially, the hull electronics layout was space inefficient leading us to be unable to fit the acoustics system inside. With the help of the Mechanical team we were able to rework the layout to be neat and allow for more internal components. This was done at the same time components were changed for high side switching of thruster power to ensure time efficiency.

### C. *Software*

Due to the probabilistic nature of computer vision systems, multiple algorithms were developed in parallel to allow the team to select the best combination directly before a competition run. To allow for simple parallel development, our robot software is architected as a collection of programs that communicate in a standardized way using the Robot Operating System. This allows us to switch out any program for an alternate one without causing friction in the overall software system. While this system allows for extreme flexibility, it adds a large amount of complexity making it difficult to onboard new software members.

To evaluate each of our potential algorithms and our software robustness as a whole, we created simulations and a novel testing framework within our simulation tools. These allowed us to create a continuous integration system. Our simulations used the Unity game engine as a base, which we chose due to its large library of documentation and user friendly tools for non-software developers. This helped us get non-software members of the club involved in simulation development. Unity does not have as high fidelity visual simulation as other tools, but we thought this was a worthwhile trade-off with ease of use.

Within Unity we developed Maktub as a plugin to simplify the process of creating automated system tests. As shown in figure 12 in Appendix A, Maktub can be used to specify spatial configurations that correspond to "Success States" and "Failure States". These states can be defined visually, which allows for rapid automated test development. These automated tests were then added to a Jenkins continuous integration server, which monitors our version control repositories and checks the performance of potential code changes as they are proposed.

Initially, a classic OpenCV approach was implemented, where edge and line detection was utilized, to visually detecting and identifying objects in pool conditions.With this approach issues with pattern, color, and shape matching arose. It was discovered that edge and line detection based code impacted SeaWolf VIII's ability to detect gate due to factors such as reflections and various foreign objects in the pool. As a result, machine learning was implemented. A sim2real approach was taken which involves taking simulation data and passing into a machine learning model along with real data and biasing. In order to incorporate real data into the machine learning model, we decapitated a YOLO v4 network and retrained the last two layers using a custom set of images of our Gate prop within a pool environment. Implementation of this method comes at the cost of less control over our code's algorithm as well as increased time need to gather data to train the model. Despite those setbacks, our sim2real approach allowed for a wide variety of scenarios and better processing of noise. As a result, we were able to successfully detect Gate because the models could identify Gate inside and outside pool conditions.

### *D. Acoustics*

The Acoustics subsystem utilizes hydrophones to capture environmental acoustic data. To process this data, we use analog circuitry, an on-board oscilloscope, and software to facilitate data logging and processing. Four channels and four hydrophones are utilized in the system. The hydrophones require a phantom power scheme along with a high impedance buffer to isolate from the other circuitry. The Acoustics system does not have a dedicated negative voltage rail and instead utilizes a specialized IC to create an Analog Ground (AGND), which is based on the total voltage range of the supply battery. To maintain the entire range of the signal captured by the hydrophones, the signal is then biased to AGND. A non inverting amplifier with a gain of 21 dB is used prior to filtering. The buffering and biasing were necessary and came as manufacturer recommendation for using their product. The amplifier stage was deemed necessary, as the low voltages received from the Pinger would see attenuation through the circuit and were not recognizable without the amplifier.

The filtering system is a Chebyshev multiple feedback topology, 8th order, band-pass filter with a band between 25kHz and 40kHz, which covers the entire range of possible Pinger frequencies. Previous iterations utilized an IC variable cutoff low pass filter, but due to cost per chip, availability, and regular issues related to over current killing the chips, this was removed in favor of a simpler, but generally more reliable, band pass filter. At the end of the circuit, a variable gain, low noise, linear amplifier IC is utilized as a final post amplifier. The low noise and low cost of this device, as well as the variable gain feature, drove its inclusion in our design. The variable gain feature's usefulness shines where it allows us to tune what the final gain should be based on testing results to avoid clipping, but still have a distinguishable signal. A detailed depiction of this design and its components can be seen in figures 14, 15, 16, and 17 in Appendix A. The completed circuit on PCB can also be seen in figure 13 in Appendix A.

For data logging, an onboard four channel USB oscilloscope is included on the robot. This gives the team a high sampling rate (80 MS/s across four channels), an 8 -bit resolution, as well as device drivers and libraries that make logging from software simpler. These features allow us to avoid the need for custom circuitry that could be lead to a failure point in the system.

Once logged, data is sent to the motherboard for processing. The first step utilizes an FFT to determine if the signal is the correct frequency, and thus our pinger. Next, cross-correlations of two sets of hydrophone data is performed to determine the time difference of the arrival based on the maximum of the resulting graph. With the time difference, an approximation of pinger location can be made using this and the distance between two hydrophones. Getting a time difference between a horizontally and vertically spaced set then allows us to use the following formula to approximate the pitch and yaw needed to face the pinger. This result is then sent out for navigation. The full formula can be seen in Appendix C.

## III. Experimental Results

### *A. Simulation*

To ensure proper functionality of the LBB system, extensive simulation was done using LTSPice before constructing the board. Pre-existing models of our gate driver chip were used to simulate the balancing of the SeaWolf VIII electronics system under some extreme conditions, such as single battery failure or current spikes. The simulations showed smooth transitions on the power supply when switching the batteries, and showed that the batteries could remain within tens of milli-volts of one another without issue. See the figure below for a snapshot of simulation testing.

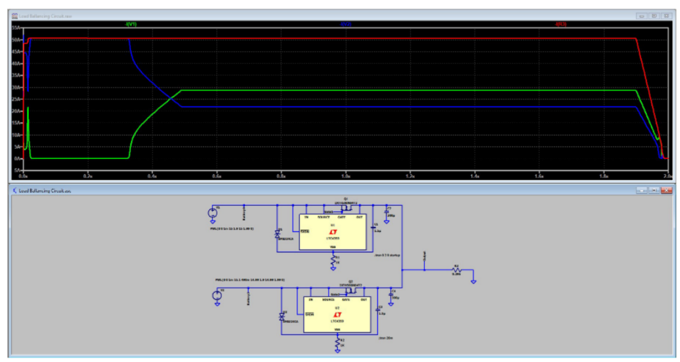

Fig. 2. LBB Simulation

LTSpice simulation was also performed on the Acoustics circuit design prior to building to ensure a proper response. The entire circuit was built, using the custom SPICE model for our op amp, and simulated across a frequency sweep. The resulting plot shows our target pass band of 25 kHz to 40 kHz. This plot can be seen in the figure 16 in Appendix A

Software systems were tested during every pool test and many adjustments were made after collecting experimental results. Before each pool test, the software team would create a plan of what should be tested in the pool, and then run these tests in our simulation system. The first major software system to be tested was our movement control system. One aspect of this system that benefited from the simulation testing was the type of input given. Our movement input to the robot consists of a 2D vector for the desired planar velocity of the robot, a scalar that gives the true desired depth of the robot and a quaternion that defines the desired angle of the robot. Another system that needed real world testing was our computer vision software. It is difficult to produce reliable simulated computer vision targets, so the team chose to rely on pool tests to collect videos which would serve as training datasets for later testing.

### *B. Pool Testing*

During the course of the last year, the team conducted monthly scheduled pool tests. This would allow us to make meaningful adjustments between test, but still get in the water frequently enough to see results and adjust goals if need be. Pool tests can be defined as leak tests, locomotion tests, vision tests, electrical tests, and acoustics tests. At times these different types of tests could run in parallel at one scheduled test day.

Leak tests were used to determine hull integrity as it relates to wet mate connectors, penetrators, and endcaps.The day prior to the pool test, the robot would be pre-sealed without electronics and a vacuum pump was used to create a 1 atmosphere pressure differential inside. At the pool, the robot would be submerged and left for 30 minutes. While submerged, swimmers would observe if obvious air bubbles were released from the robot hull. If so this indicates a leak. After the 30 minutes, the robot is surfaced, unsealed, and the team would check leak tape and for moisture in the hull. Leaks could be observed if the leak tape was red, as seen below, or if the pressure differential during vacuum test increased by 300 Pascals or less in 8 hours.

Locomotion tests were used to ensure robot engaged in stable and intentional movement. To determine this, the thrusters would be dry run to confirm signal was being received from software. Additionally, at the pool the robot would be instructed to dive, move in a straight line, and spin according to a mission. If the mission plan was followed with stable yaw, pitch, and roll and no incorrect movements occurred, the test was deemed successful. If issues arose, PID tuning was attempted at the test. RViz, a ROS subpackage allowing for visualizing system behavior, enabled the team to understand the robot's actions in water.

Vision tests were used to determine whether the robot could identify task objects such as Gate. In these tests, classic edge and line detection or machine learning code was implemented. The robot would be oriented with cameras pointed directly at the object, usually Gate, and upon identification would navigate toward the object. The initial use of edge and line detection saw regular failure due to reflections and other objects in the pool. This led us to training machine learning models. For example, on the left we see the edge detection model perceiving foreign objects, in this case a ladder, as Gate and on the right we see the machine learning model visualizing and properly labeling Gate.

If the robot navigates correctly and/or cases passes through Gate, it would be deemed a successful test. In these tests, locomotion was also observed and tuned as needed.

Electrical pool testing was mainly targeted at our Load Balancing Board to determine if it could withstand full thruster load. Thrusters would be run and the team would observe if any electrical failures occurred during missions. Typically this could be done in parallel with other pool test goals, such as locomotion and vision as they both would put strain on thrusters and the Load Balancing Board.

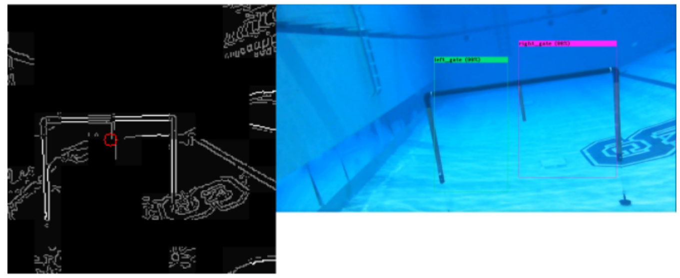

Fig. 3. Classical OpenCV Results vs Machine Learning Results

Acoustics tests were done to ensure the working system from hydrophones, to filtering, to scope, and to computer. Since the robot was in a constant state of development, it hindered the ability to test the acoustics system and in response an independent pool testing platform, ”Paddle Dog”, was made to specifically house acoustics electronics and hydrophones. Testing was done with a pinger to determine if hydrophones functioned, circuitry was working properly, and if the computer was logging data through the scope accurately. Following runs, data would be analyzed and compared to expectations of a known ping waveform. Below is an example of what data collected from one hydrophone looks like including an FFT showing the frequency of the captured signal. Reference figure 15 in Appendix A, to see detailed depiction of the design of Paddle Dog.

## IV. ACKNOWLEDGEMENTS

The Underwater Robotics Club is housed within North Carolina State University's Electrical and Computer Engineering department. We would like to thank the faculty and staff who have supported and continue to support the club. Special thanks to Dr. John Muth and Dr. John-Paul Ore for advising the club, as well as Carmichael Gymnasium for providing us a facility for testing. Lastly, we would like to extend our gratitude to our sponsors for providing us access to their technical products for helping us design and develop the robot.

- Fischer Connectors
- Altium Designer
- Advanced Circuits
- NVIDA
- Igus
- Raise3D Technologies
- JW Fishers
- KB Custom Metalworks
- North Carolina Space Grant
- NC State University Student Government Association
- Engineer's Council at NC State University
- NC State University Engineer Your Experience Program

## REFERENCES

[1] M. Quigley, K. Conley, B. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, and A. Ng, "Ros: an open-source robot operating system," vol. 3, 01 2009.

[2] N. Koenig and A. Howard, "Design and use paradigms for gazebo, an open-source multi-robot simulator," in IEEE/RSJ International Confer ence on Intelligent Robots and Systems, Sendai, Japan, Sep 2004, pp. 2149–2154.

[3] C. R. Harris, K. J. Millman, S. J. van der Walt, R. Gommers, P. Virtanen, D. Cournapeau, E. Wieser, J. Taylor, S. Berg, N. J. Smith, R. Kern, M. Picus, S. Hoyer, M. H. van Kerkwijk, M. Brett, A. Haldane, J. F. del R´ıo, M. Wiebe, P. Peterson, P. Gerard-Marchant, ´ K. Sheppard, T. Reddy, W. Weckesser, H. Abbasi, C. Gohlke, and T. E. Oliphant, "Array programming with NumPy," Nature, vol. 585, no. 7825, pp. 357–362, Sep. 2020. [Online]. Available: https://doi.org/10.1038/s41586-020-2649-2

[4] G. Bradski, "The OpenCV Library," Dr. Dobb's Journal of Software Tools, 2000.

[5] "Air Leak Test equivalent to ipx7and IPX8 - fukuda-jp.com." [Online]. Available: https://www.fukuda-jp.com/en/msz/pdf/Calculation_of_leak_amount(E)_01.pdf.

[6] J. Amesz, "Conversion of leak flow-rates for various fluids and different pressure ..." [Online]. Available: https://aei.pitt.edu/91144/1/2982.pdf.

[7] A. Iyengar, "Acoustics Derivation", [Online]. Available: https://ncsurobotics.org/wiki/index.php/Documentation-_Acoustics

## V. Appendix A - Schematics and Diagrams

Below are schematics and diagrams not included in the body of the TDR but aid in visualizing the concepts discussed in the paper. Figures 4 through 17 are discussed in the Design Creativity section while Figures 18 through 20 are discussed in the Experimental Results section.

Fig. 4. Render of mounted singular waterproof battery hull for a single LiPo battery

Fig. 5. Render of hinge locking doors on SeaWolf VIII

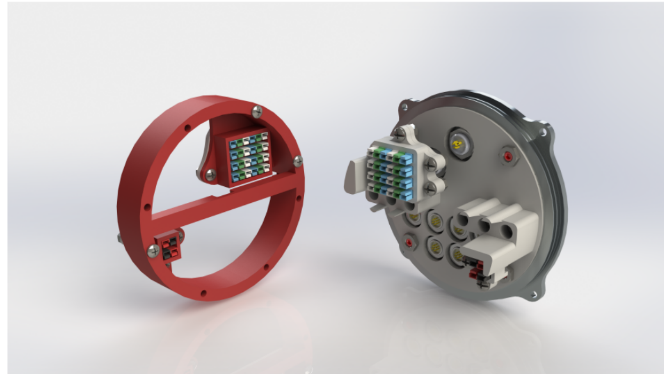

Fig. 6. Render of endcap interface of SeaWolf VIII

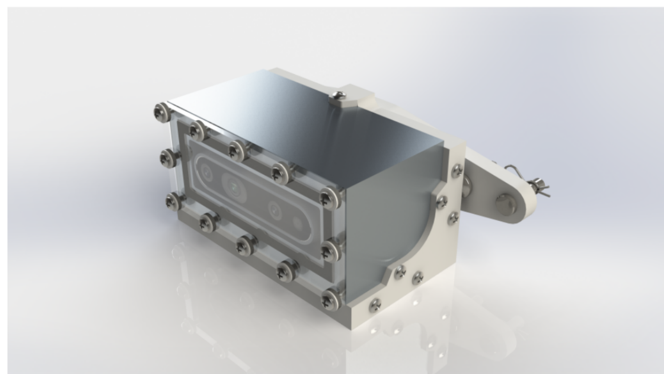

Fig. 7. Render of assembled camera enclosure with camera inside

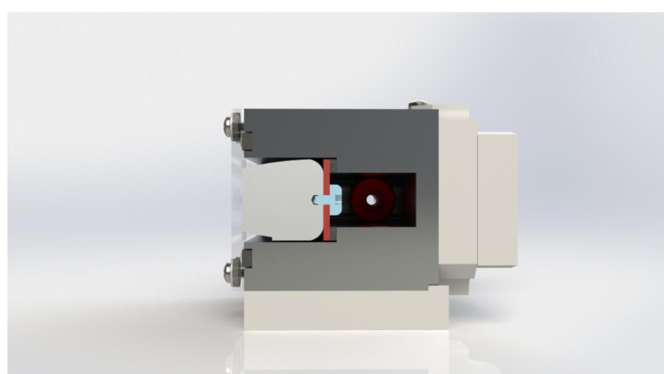

Fig. 8. Render of cross-section of assembled camera enclosure with camera inside

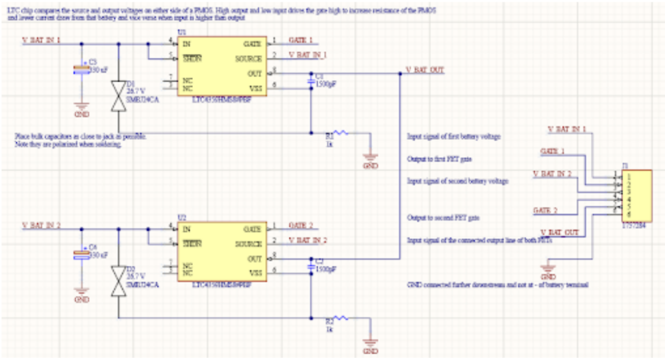

Fig. 9. LBB Schematic

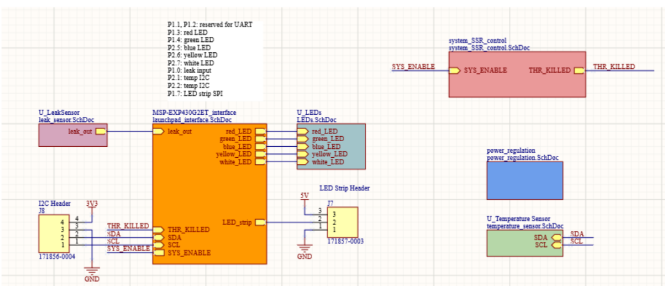

Fig. 10. MEB Schematic

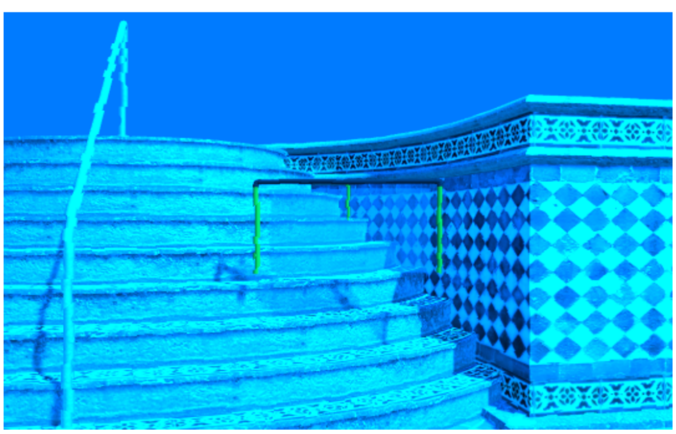

Fig. 11. Simulation of Gate in Unity

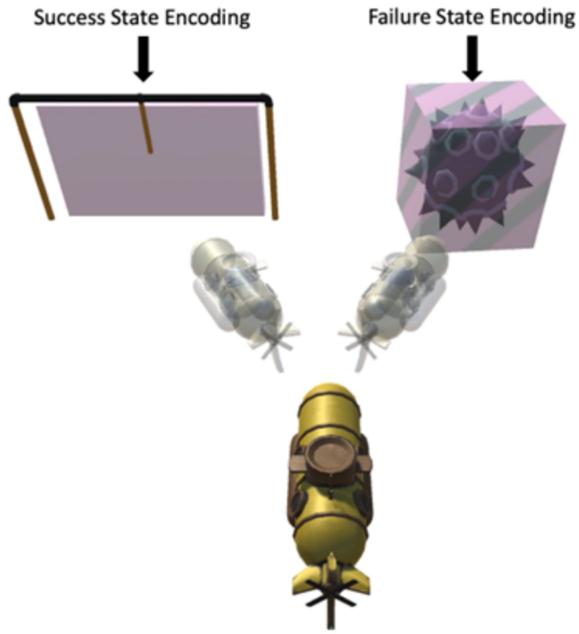


Fig. 12. Maktub Spatial Configurations

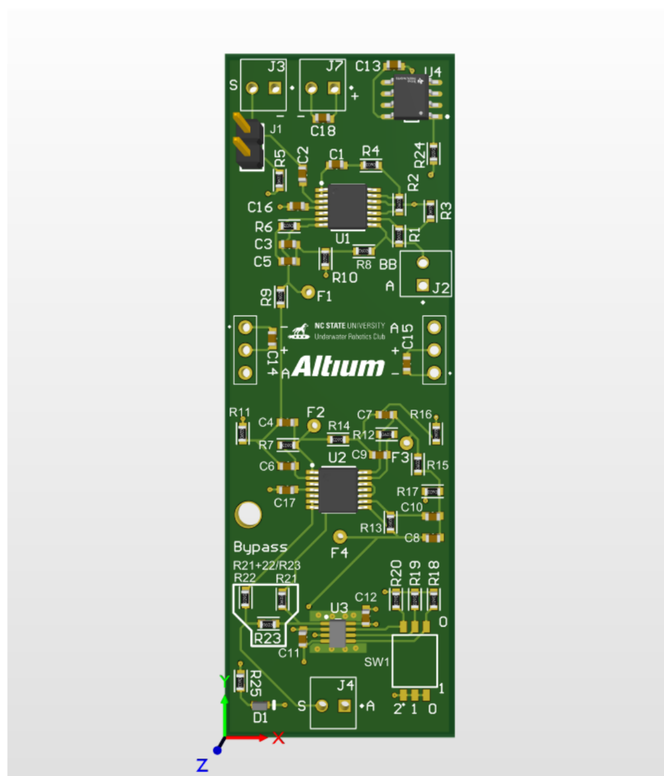


Fig. 13. Acoustics PCB

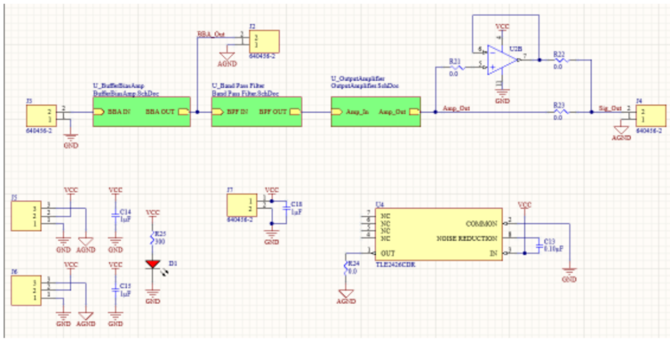

Fig. 14. Acoustics High Level Channel Schematic

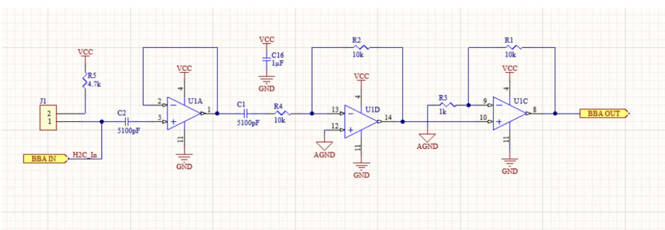

Fig. 15. Acoustics Buffer Bias Amp Circuit

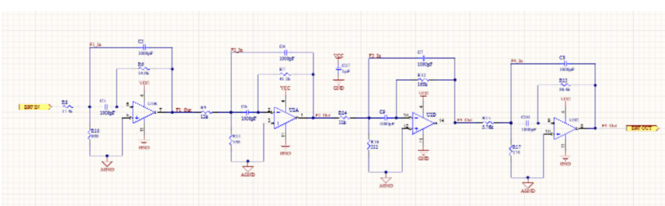

Fig. 16. Acoustics Band Pass Filter Schematic

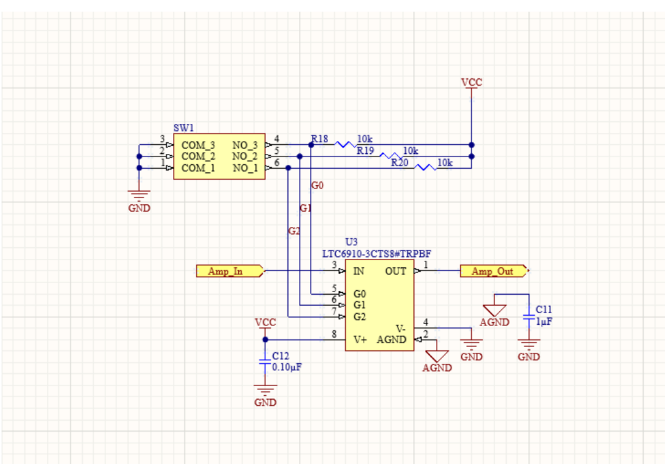


Fig. 17. Acoustics Amplifier Schematic

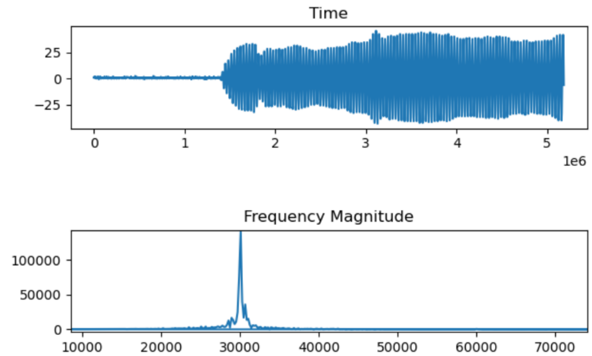


Fig. 18. Ping Data From Acoustics Pool Test

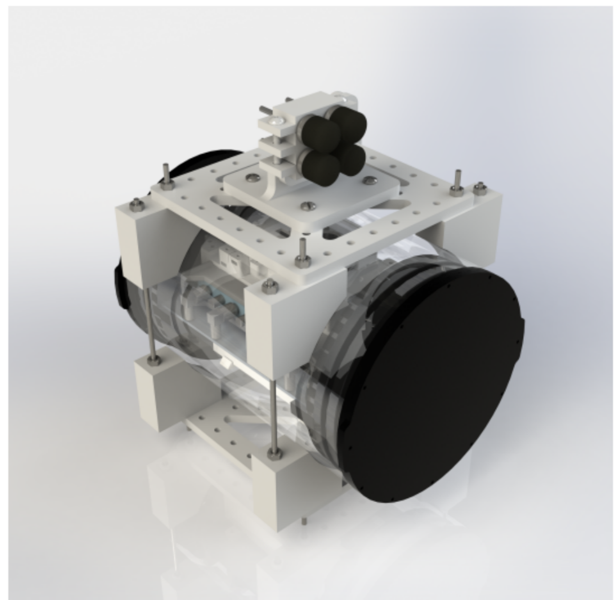

Fig. 19. Render of Paddle Dog

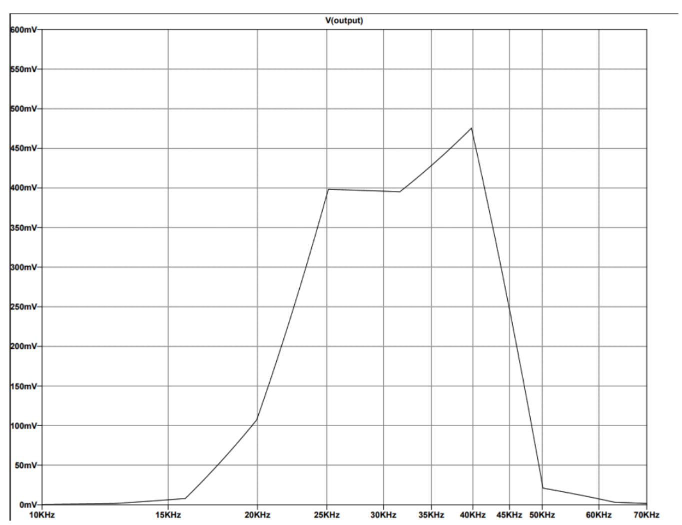


Fig. 20. Bode Plot of Target Pass Band of 25 kHz to 40 kHz

## VI. Appendix B - Hull Material Pugh Matrix

Appendix B contains the Hull Material Pugh Matrix used to determine the optimal material for the main hull of SeaWolf VIII. The materials considered include extruded aluminum, cast acrylic, and extruded polycarbonate.

| | | Hull Materials | | | | | |
|---|---|---|---|---|---|---|---|
| | | A | | B | | C | |
| | | Cast Acrylic | | Extruded Aluminum | | Extruded Polycarbonate | |
| **Selection Criteria** | **Weight** | **Rating (1-5)** | **Weighted Score** | **Rating (1-5)** | **Weighted Score** | **Rating (1-5)** | **Weighted Score** |
| **Dimensional** | 20 | | | | | | |
| Good tolerances | 12 | 4 | 48 | 4 | 48 | 3 | 36 |
| Low CTE | 8 | 3 | 24 | 5 | 40 | 3 | 24 |
| **Structural** | 35 | | | | | | |
| Strength | 12 | 4 | 48 | 5 | 60 | 3 | 36 |
| Elasticity (crack resistance) | 12 | 2 | 24 | 4 | 48 | 5 | 60 |
| Scratch resistance | 4 | 3 | 12 | 3 | 12 | 2 | 8 |
| Impact resistance | 7 | 4 | 28 | 3 | 21 | 5 | 35 |
| **Monetary** | 5 | | | | | | |
| Low cost | 5 | 2 | 10 | 4 | 20 | 3 | 15 |
| **Functional** | 25 | | | | | | |
| Thermal conductivity | 5 | 1 | 5 | 5 | 25 | 1 | 5 |
| Chlorine resistance | 12 | 5 | 60 | 5 | 60 | 2 | 24 |
| Electrically insulating | 5 | 5 | 25 | 1 | 5 | 5 | 25 |
| High Weight | 3 | 1 | 3 | 4 | 12 | 1 | 3 |
| **Convenience** | 15 | | | | | | |
| Low Weight | 3 | 5 | 15 | 2 | 6 | 5 | 15 |
| Transparency | 12 | 5 | 60 | 1 | 12 | 4 | 48 |
| | Total Score | | **314** | | **321** | | **298** |
| | **Rank** | | **2** | | **1** | | **3** |

Fig. 21. Table of Hull Material Pugh Matrix

# VII. Appendix C - Acoustics TDOA Location Estimation Formula

Appendix C contains a partial derivation of the TDOA location estimation formula. The Full Derivation of these variables and values as well as explanation can be found in Reference 7.

$$C_1 = \frac{{d_1}^2}{\delta x^2 - {d_1}^2}$$

$$C_2 = \frac{{d_2}^2}{\delta z^2 - {d_2}^2}$$

$$\theta = \tan^{-1}\sqrt{\frac{C_1 + C_1 C_2}{1 - C_1 C_2}}$$

$$\phi = \tan^{-1}\sqrt{\frac{C_1 + 1}{C_2 + C_1 + C_2}}$$

## VIII. Appendix D - System and Simulation Test Time Table

Appendix D contains tables of the System and Simulation Test Table where Figure 22 is the legend of the System and Simulation Test Time Table, Figure 23 is a table totaling the hours spent testing and simulating, and Figure 24 is a table detailing the dates on each test.

| Legend of System and Simulation Test Table | |
|---|---|
| Test | Application |
| Acoustics Test | Consists of testing how well acoustics circuits can detect and process pings at pool tests with the Paddle Dog platform. This helps determine if acoustics system can detect and process pings in an environment similar to the RoboSub competition. |
| Bucket Test | Consists of testing improved circuits and filtering code in a semi-large bucket of water that contains the pinger and hydrophone. Allows for rapid testing and acoustic system modification. Performed at least once a week. |
| Leak Tests | Consists of sealing the robot and submerging it in an 11 ft pool for 30 minutes to monitor for leaking of waterproof enclosures. Performed when major changes/additions to the waterproof enclosures has occurred. |
| Load-Balancing-Board Test | Consists of placing the load of the thrusters on the LBB |
| Locomotion Test | Consists running a series of mission fill with instructed directions and movement to confirm there is accurate communication between the computer, flight controller, and thrusters. |
| Simulation | Consists of running mission and vision code through a simulated environment including a pool, robot, and tasks at RoboSub. Typically a 30 minute session done twice a week that consists of both running simulation and debugging. On many occasions issues found in code was debugged/improved outside of that timeframe and simulated again. |
| System Dry Run | Will occur before each pool test and after major changes to the electrical system has been made. Longer sessions would consists are doing checks on all of the electrical subsystems to ensure expected output was occurring. Longer checks would consists of not only checking the electrical system but also running thrusters to ensure proper communication as well as recalibrating thrusters when needed. |
| Computer Vision Test | Consists of running launch programs where the robot would take visual input based on computer vision code and act according to the mission code. Both classic OpenCV and machine learning code was run. |

Fig. 22. Legend of System and Simulation Test Table

| Hours Spent Testing and Simulating | | |
|---|---|---|
| | To-Date | Planned |
| Acoustics | 44 | 65 |
| Bucket Test | 44 | 49 |
| Leak Tests | 8 | 11 |
| Load -Balancing-Board Test | 5 | 5 |
| Pool Tests (Locomotion & Computer Vision) | 37 | 61 |
| Simulation | 40 | 45 |
| System Dry Run | 13.5 | 18 |
| Total | 191.5 | 254 |

Fig. 23. Hours Spent Testing and Simulating

| System and Simulation Test Time Table | | | | |
|---|---|---|---|---|
| Implemented Test | Date | Time | Hours | Goal/Reason |
| System Dry Run | Wednesday, August 25th, 2021 | 7:30 pm - 8:30 pm | 0.5 | Reference Legend |
| System Dry Run | Friday, August 27th, 2021 | 7:30 pm - 8:30 pm | 1 | Reference Legend |
| Full Robot Test | Saturday, August 28th, 2021 | 10 am - 3 pm | 5 | - Locomotion Test: Performing locomotion tests on robot with updated pixhawk communication code<br>- Acoustics Test: Standard Test with acoustics breadboard circuit in Paddle Dog |
| Acoustics | Friday, October 22nd, 2021 | 1 pm - 3 pm | 2 | - Acoustics Test: Standard Test with acoustics breadboard circuit in Paddle Dog |
| System Dry Run | Wednesday, October 27th, 2021 | 7:30 pm - 8:30 pm | 0.5 | Reference Legend |
| System Dry Run | Friday, October 29th, 2021 | 7:30 pm - 8:30 pm | 1 | Reference Legend |
| Full Robot Test | Sunday, October 31st, 2021 | 10 am - 3 pm | 5 | - Locomotion Test: PID tuning and debugging of Pixhawk drift issue<br>- Computer Vision Test - Retrieve Gate Footage and Test Classic OpenCV code for Gate<br>- Acoustics Test: Standard Test with acoustics breadboard circuit in Paddle Dog |
| System Dry Run | Wednesday, November 10th, 2021 | 7:30 pm - 8:30 pm | 0.5 | Reference Legend |
| System Dry Run | Friday, November 12th, 2021 | 7:30 pm - 8:30 pm | 1 | Reference Legend |
| Full Robot Test | Saturday, November 13th, 2021 | 10 am - 3 pm | 5 | - Locomotion Test: Quick check to ensure autonomous motion is operating as expected<br>- Computer Vision Test - Retrieve Gate Footage and Test Classic OpenCV code for Gate<br>- Acoustics Test: Standard Test with acoustics breadboard circuit in Paddle Dog |

| | | | | |
|---|---|---|---|---|
| System Dry Run | Wednesday, January 19th, 2022 | 7:30 pm - 8:30 pm | 0.5 | Reference Legend |
| System Dry Run | Friday, January 21st, 2022 | 7:30 pm - 8:30 pm | 1 | Reference Legend |
| Full Robot Test | Saturday, January 22nd, 2022 | 10 am - 3 pm | 5 | - Load-Balancing-Board Test<br>- Acoustics Test: Standard Test with acoustics breadboard circuit in Paddle Dog |
| System Dry Run | Wednesday, February 16th, 2022 | 7:30 pm - 8:30 pm | 0.5 | Reference Legend |
| System Dry Run | Friday, February 18th, 2022 | 7:30 pm - 8:30 pm | 1 | Reference Legend |
| Full Robot Test | Sunday, February 20th, 2022 | 10 am - 3 pm | 5 | - Locomotion Test: Quick check to ensure autonomous motion is operating as expected<br>- Computer Vision Test: Retrieve Gate Footage and Test Classic OpenCV code for Gate<br>- Acoustics Test: Standard Test with acoustics breadboard circuit in Paddle Dog |
| System Dry Run | Wednesday, March 3rd, 2022 | 7:30 pm - 8:30 pm | 0.5 | Reference Legend |
| System Dry Run | Friday, March 5th, 2022 | 7:30 pm - 8:30 pm | 1 | Reference Legend |
| System Leak Test | Sunday, March 6th, 2022 | 10 am - 2 pm | 4 | Addition of Aluminum Hull<br>- Acoustics Test: Standard Test with acoustics breadboard circuit in Paddle Dog |
| System Dry Run | Wednesday, March 9th, 2022 | 7:30 pm - 8:30 pm | 0.5 | Reference Legend |
| System Dry Run | Friday, March 11th, 2022 | 7:30 pm - 8:30 pm | 1 | Reference Legend |
| System Leak Test | Saturday, March 12th, 2022 | 10 am - 2 pm | 4 | Leak test because battery and aluminum hulls |
| System Dry Run | Wednesday, March 23rd, 2022 | 7:30 pm - 8:30 pm | 0.5 | Reference Legend |
| System Dry Run | Friday, March 25th, 2022 | 7:30 pm - 8:30 pm | 1 | Reference Legend |

| | | | | |
|---|---|---|---|---|
| Full Robot Test | Sunday, March 27th, 2022 | 10 am - 4 pm | 6 | - Locomotion Test: Quick check to ensure autonomous motion is operating as expected<br>- Computer Vision Test: Test Classic OpenCV for Gate code<br>Locomotion -<br>- Acoustics Test: Standard Test with acoustics breadboard circuit in Paddle Dog |
| System Dry Run | Wednesday, April 13th, 2022 | 7:30 pm - 8:30 pm | 0.5 | Reference Legend |
| System Dry Run | Friday, April 15th, 2022 | 7:30 pm - 8:30 pm | 1 | Reference Legend |
| Full Robot Test | Saturday, April 16th, 2022 | 10 am - 4 pm | 6 | - Locomotion Test: Quick check to ensure autonomous motion is operating as expected<br>- Computer Vision: Test machine learning code for Gate and retrieve ML training data of Gate<br>- Acoustics Test: Standard Test with acoustics breadboard circuit in Paddle Dog |
| Acoustics | Saturday, June 11th, 2022 | 10 am - 4 pm | 6 | Acoustics Test - Standard Test |
| Leak Test and Acoustics | Saturday, June 18th, 2022 | 10 am - 1 pm | 3 | - Leak test additions of wet mate connectors that replaced penetrator connectors of 6 thrusters with wet mate connectors<br>- Acoustics Test: Standard Test with singular acoustics PCB in Paddle Dog |
| System Dry Run | Wednesday, June 22nd, 2022 | 7:30 pm - 8:30 pm | 0.5 | Reference Legend |
| System Dry Run | Friday, June 24th, 2022 | 7:30 pm - 8:30 pm | 1 | Reference Legend |
| Full Robot Test | Saturday, June 25th, 2022 | 10 am - 4 pm | 6 | - Locomotion Test: Quick check to ensure autonomous motion is operating as expected<br>- Computer Vision Test: Test machine learning code and retrieve footage for Path and Buoys<br>- Acoustics Test: Standard Test with all four acoustics PCBs in Paddle Dog |

| | | | | |
|---|---|---|---|---|
| System Dry Run | Wednesday, July 13th, 2022 | 7:30 pm - 8:30 pm | 0.5 | Reference Legend |
| System Dry Run | Friday, July 15th, 2022 | 7:30 pm - 8:30 pm | 1 | Reference Legend |
| Full Robot Test | Saturday, July 16th, 2022 | 10 am - 4 pm | 6 | - Locomotion Test: Quick check to ensure autonomous motion is operating as expected<br>- Computer Vision Test: Test Machine Learning and Classic OpenCV code for Gate, Path, Buoys<br>- Acoustics Test: Standard Test with all four acoustics PCBs in SeaWolf VIII |
| System Dry Run | Wednesday, July 20th, 2022 | 7:30 pm - 8:30 pm | 0.5 | Reference Legend |
| System Dry Run | Friday, July 22nd, 2022 | 7:30 pm - 8:30 pm | 1 | Reference Legend |
| Full Robot Test | Saturday, July 23rd, 2022 | 10 am - 4 pm | 6 | - Locomotion Test: Quick check to ensure autonomous motion is operating as expected<br>- Computer Vision Test: Test Machine Learning and Classic OpenCV code for Gate, Path, Buoys<br>- Acoustics Test: Standard Test with all four acoustics PCBs in SeaWolf VIII |

Figure 24: Pool and Simulation Test Dates

# VII. APPENDIX E - COMPONENT SPECIFICATIONS

| Component | System | Vendor | Model/Type | Specs | Quantity | Custom/Purchased |
|---|---|---|---|---|---|---|
| Ubuntu (Linux OS) | Software | Canonical Ltd. | 20.04 | -- | -- | Installed |
| tmux | Software | ISC license | 3.2 | -- | -- | Installed |
| ROS 1 | Software | ROS | Neotic | -- | -- | Installed |
| Unity | Software | Unity Technologies | 2020.3.30f1 | -- | -- | Installed |
| OpenCV | Software | 3-clause BSD license | 4 | -- | -- | Installed |
| YOLOv4 | Software | Darknet | v4 | -- | -- | Installed |
| MAVROS | Software | ROS | Neotic | -- | -- | Installed |
| Python | Software | Python Software Foundation | 3.00 | -- | -- | Installed |
| C# | Software | Microsoft | 10 | -- | -- | Installed |
| C | Software | ISO/IEC JTC 1 | 20 | -- | -- | Installed |
| C++ | | | 17 | -- | -- | Installed |
| ArduSub | Software | ArduPilot Development Team and Community | v4 | -- | -- | Installed |
| QGroundControl | Software | Dronecode Foundation | 4.00 | -- | -- | Installed |
| Perforated Aluminum Side 1 | Frame | Custom KB Metalworks | -- | 8 x 10.48 x 0.250 in | 4 | Custom |
| Perforated Aluminum Side 2 | Frame | Custom KB Metalworks | -- | 10 x 10.5 x 0.250 in | 2 | Custom |
| Hull Cradle | Frame | Custom KB Metalworks | -- | 10.75 x 10.75 x 0.250 in Perforated Aluminum with 8 in diameter | 4 | Custom |
| | Frame | Custom KB Metalworks | -- | 24" x 10" with angle | 4 | Custom |
| Battery Hull Threaded Rod | Frame | McMaster-Carr | -- | 0.25x9.25 in | 8 | Purchased and |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | Customized |
| Main Hull Threaded Rod | Frame | McMaster-Carr | -- | 0.25x25.75 in | 4 | Purchased and Customized |
| Main Hull | Waterproof Housing | OnlineMetals | -- | 8.00x23.88 in Aluminum Tube | 1 | Custom |
| Battery Hull | Waterproof Housing | OnlineMetals | -- | 4.00x8.00 in Aluminum Tube | 2 | Custom |
| Main Hull Endcap | Waterproof Housing | Mecha Inc | -- | 8 in diameter | 2 | Custom |
| Battery Hull Endcap | Waterproof Housing | Mecha Inc | -- | 4 in diameter | 4 | Custom |
| Main Hull Endcap O-Ring | Waterproof Housing | Amazon | -- | 8 in diameter | 4 | Purchased |
| Battery Hull Endcap O-ring | Waterproof Housing | Amazon | -- | 4 in diameter | 8 | Purchased |
| Camera Enclosure | Waterproof Housing | Star Rapid | -- | -- | 2 | Custom |
| Acrylic | Waterproof Housing | McMaster-Carr | -- | -- | 2 | Custom |
| Gasket | Waterproof Housing | McMaster-Carr | -- | -- | 2 | Purchased and Customized |
| MOAB Platform | Waterproof Housing | Custom KB Metalworks | -- | -- | 1 | Purchased and Customized |
| Pool Noodles | Buoyancy Control | Amazon | -- | 5" | 1 | Purchased and Customized |
| Weights | Buoyancy Control | -- | -- | 3 lbs | 3 | Purchased |
| Thruster SSR | Power | Mouser | SSR D1D80 | 1 VDC to 100 VDC/ 80 A | 1 | Purchased |
| System SSR | Power | Mouser | SSR D1D80 | 1 VDC to 100 VDC/ 80 A | 1 | Purchased |
| Power Bar Mount | Power | In-House | -- | -- | | Custom |

| | | | | | | |
|---|---|---|---|---|---|---|
| Load Balancing Board | Power | In-House | -- | -- | 1 | Custom |
| PP Power Distribution | Power | Powerwerx | PD-8 | 3.75"W x 0.97"D x 1.32"H 58VDC/45A | 1 | Purchased |
| Graphene Professional 10V LiPo | Power | HobbyKing | 9067000296-0 | 10000mAh/4S1P / 4 Cell / 14.8V 168x69x40mm | 2 | Purchased |
| 5V Regulator for USB Hub | Power | Adafruit | MP2307 | 5V @ 3A | 1 | Purchased |
| Jetson Regulator | Power | Amazon | 8-40T5-5A | DC 8~40V to 5V 5A 3.31" x 1.81" x 0.71" | 1 | Purchased |
| Cube Orange Regulator | Power | IRLock | -- | -- | 1 | Purchased |
| System Switch - | Power | Mouser | M2023TJW01-GA-4A-CF | M-2023 6A.125V.AC | 1 | Purchased |
| MOSFETs | Power | -- | -- | -- | 2 | Purchased |
| In-line fuse | Power | -- | -- | -- | 2 | Purchased |
| Thruster | Motor Controls | Blue Robotics | T200 | -- | 8 | Purchased and Customized |
| Fuse Bar | Motor Controls | Blue Sea Systems | ST Blade ATO/ATC Fuse Blocks 8 circ, no cover | 8.94 x 1.65 x 1 inches 32V | 1 | Purchased |
| Fuses | Motor Controls | Digikey | F5101-ND | 20 amp | 8 | Purchased |
| ESCs | Motor Controls | Blue Robotics | | 7-26V/30A | 8 | Purchased |
| GND Bar | Motor Controls | Blue Sea Systems | 150A, 10 screw, No cover | 2 x 3.5 x 11 inches | 1 | Purchased |
| Killswitch | Motor Controls | McMaster-Carr | 8002K71 | 15 A @ 125 V AC, 12 A @ 28 V DC | 1 | Purchased |
| Jetson Nano | System Controls | Nvidia | 945-13450-0000-100 | 2.72 x 1.77 x 1.77 inches | 1 | Purchased |
| Cube Orange | System Controls | IRLock | HX4-06159 | 4-5.7 V/250 mA | 1 | Purchased |
| Main Electronics Board | System Controls | In-House | -- | -- | 1 | Custom |

| | | | | | | |
|---|---|---|---|---|---|---|
| IMU | System Controls | Adafruit | MPU-6050 | 26.0mm x 17.8mm x 4.6mm | 1 | Purchased |
| Stemma QT Cable (for IMU) | System Controls | Adafruit | JST-SH | 100mm | 1 | Purchased |
| Stemma QT Cable (for IMU) | System Controls | Adafruit | JST-SH | 400mm | 1 | Purchased |
| Stemma QT to Male Dupont | System Controls | Adafruit | JST-SH | 150mm | 1 | Purchased |
| Stemma QT to Female Dupont | System Controls | Adafruit | JST-SH | 150mm | 1 | Purchased |
| 64 GB mini SD card | System Controls | Amazon | -- | -- | 1 | Purchased |
| MSP430 Launchpad | Main Electronics Board v1.2 | Digikey | MSP-EXP430FR2311 | 16-bit MCU with 4KB FRAM | 1 | Purchased and Customized |
| Ceramic Capacitor X7R | Main Electronics Board v1.2 | Digikey | CC0805JPX7R9BB104 | 0.1 µF ±5% 50V 0805 | 5 | Purchased |
| Ceramic Capacitor X5R | Main Electronics Board v1.2 | Digikey | CL21A106KAYNNNE | 10 µF ±10% 25V 0805 | 5 | Purchased |
| Ceramic Capacitor X5R | Main Electronics Board v1.2 | Digikey | CL21A226MAYNNNE | 22 µF ±20% 25V 0805 | 6 | Purchased |
| Ceramic Capacitor X7R | Main Electronics Board v1.2 | Digikey | CL21B105KAFNNNE | 1 µF ±10% 25V 0805 | 5 | Purchased |
| LED BLUE CLEAR | Main Electronics Board v1.2 | Digikey | 150080BS75000 | 0805 SMD | 1 | Purchased |
| LED RED CLEAR | Main Electronics Board v1.2 | Digikey | 150080SS75000 | 0805 SMD | 1 | Purchased |
| LED GREEN CLEAR | Main Electronics Board v1.2 | Digikey | 150080GS75000 | 0805 SMD | 1 | Purchased |
| PTC RESET FUSE | Main Electronics Board v1.2 | Digikey | MF-MSMF160-2 | 30V 50MA 1210 | 1 | Purchased |

| | | | | | | |
|---|---|---|---|---|---|---|
| PTC RESET FUSE | Main Electronics Board v1.2 | Digikey | MF-USMF005-2 | 30V 50MA 1210 | 1 | Purchased |
| CONN HEADER R/A | Main Electronics Board v1.2 | Digikey | 430451000 | 10POS 3MM | 1 | Purchased |
| CONN RECEPT | Main Electronics Board v1.2 | Digikey | 430251000 | 10POS 3MM VERT DUAL | 1 | Purchased |
| CONN SOCKET | Main Electronics Board v1.2 | Digikey | 430300002 | 20-24AWG CRIMP GOLD | 1 | Purchased |
| FIXED IND 4.3UH | Main Electronics Board v1.2 | Digikey | SRP6050CA-4R3M | 9A 16.2 MOHM SMD | 1 | Purchased |
| SSQ-110-03-F-S | Main Electronics Board v1.2 | Mouser | SSQ-110-03-F-S | 10 POS, 2.54 mm | 1 | Purchased |
| SSQ-102-03-G-S | Main Electronics Board v1.2 | Mouser | SSQ-102-03-G-S | 2 POS, 2.54 mm | 1 | Purchased |
| MOSFET N-CH | Main Electronics Board v1.2 | Mouser | NX7002BKR | 60V 270MA TO236AB | 1 | Purchased |
| MOSFET N-CH | Main Electronics Board v1.2 | Mouser | 2N7000 | 60V 200MA TO92-3 | 1 | Purchased |
| Resistor 1 | Main Electronics Board v1.2 | Digikey | RC0805FR-07100RL | 100 OHM 1% 1/8W 0805 | 5 | Purchased |
| Resistor 2 | Main Electronics Board v1.2 | Digikey | RC0805JR-0710KL | 10K OHM 5% 1/8W 0805 | 8 | Purchased |
| Resistor 3 | Main Electronics Board v1.2 | Digikey | RC0805FR-0752K3L | 52.3K OHM 1% 1/8W 0805 | 5 | Purchased |
| Resistor 4 | Main Electronics Board v1.2 | Digikey | RK73B2ATTD132J | 1.3K OHM 5% 1/4W 0805 | 5 | Purchased |
| Resistor 5 | Main Electronics Board v1.2 | Digikey | RC0805FR-07140RL | 140 OHM 1% 1/8W 0805 | 9 | Purchased |

| | | | | | | |
|---|---|---|---|---|---|---|
| Resistor 6 | Main Electronics Board v1.2 | Digikey | RC0805FR-0710RL | 10 OHM 1% 1/8W 0805 | 7 | Purchased |
| Resistor 7 | Main Electronics Board v1.2 | Digikey | RMCF0805FT100K | 100K OHM 1% 1/8W 0805 | 6 | Purchased |
| Resistor 8 | Main Electronics Board v1.2 | Digikey | RT0805FRE074K7L | SMD 4.7K OHM 1% 1/8W 0805 | 5 | Purchased |
| SWITCH TACTILE, SPST-NO | Main Electronics Board v1.2 | Digikey | FSM2JSMA | 0.05A 24V | 2 | Purchased |
| IC REG LINEAR, SOT23-5 | Main Electronics Board v1.2 | Digikey | AP2139AK-3.3TRG1 | 3.3V 250MA | 1 | Purchased |
| DCDC CONV HV BUCK, SOT563 | Main Electronics Board v1.2 | Digikey | AP62301Z6-7 | T&R 3K | 1 | Purchased |
| Leak Sensor | Main Electronics Board v1.2 | In-House | -- | -- | 1 | Custom |
| C1, C3 | Main Electronics Board v1.2 | Kemet | -- | C0805C106K8PACTU | 2 | Purchased |
| F1 | Main Electronics Board v1.2 | Littelfuse Inc | 0466001.NR | FUSE BOARD MNT 2A 63VAC/VDC 1206 | 1 | Purchased |
| F2 | Main Electronics Board v1.2 | Littelfuse Inc | -- | FUSE BOARD MNT 1A 63VAC/VDC 1206 | 1 | Purchased |
| J1, J3, J7 | Main Electronics Board v1.2 | Würth Elektronik | -- | Connector | 3 | Purchased |
| J2, J4, J6 | Main Electronics Board v1.2 | Würth Elektronik | -- | Connector | 3 | Purchased |
| J5 | Main Electronics Board v1.2 | Würth Elektronik | 67996-406HLF | CONN HEADER VERT 2x3POS 2.54MM | 1 | Purchased |

| | | | | | | |
|---|---|---|---|---|---|---|
| J8 | Main Electronics Board v1.2 | Würth Elektronik | -- | Connector | 1 | Purchased |
| J9 | Main Electronics Board v1.2 | Würth Elektronik | -- | Header, 4-Pin, Dual row | 1 | Purchased |
| J10 | Main Electronics Board v1.2 | Würth Elektronik | 61300411121 | CONN HEADER VERT 4POS 2.54MM | 1 | Purchased |
| Q2, Q3 | Main Electronics Board v1.2 | On Semiconductor | 2N7000 | MOSFET N-CH 60V 200MA TO92-3 | 2 | Purchased |
| Q4 | Main Electronics Board v1.2 | On Semiconductor | -- | MOSFET P-CH 40V 175MA TO92-3 | 1 | Purchased |
| R17, R18, R19, R20, R21 | Main Electronics Board v1.2 | Yageo | -- | Chip Resistor, 1 KOhm, +/- 1%, 125 mW, | 5 | Purchased |
| R1, R2 | Load Balancing Board | Panasonic Electronic Components | SMD-0805-RES | RES SMD 1K OHM 1% 1/2W | 2 | Purchased |
| D1, D2 | Load Balancing Board | Littelfuse | Zenor Diode - duplicate | TVS DIODE 24VWM 38.9VC DO214AA | 2 | Purchased |
| C3, C4 | Load Balancing Board | Panasonic Electronic Components | CAPPRD350W65 D800H2200 | Aluminum Electrolytic Capacitors - Radial Leaded Al Lytic CapLow ESR Radial FM Series | 2 | Purchased |
| C1, C2 | Load Balancing Board | Murata Electronics North America | SMD-0805C | CAP CER 1500PF 50V X7R 0805 | 2 | Purchased |
| J1 | Load Balancing Board | Phoenix Contact | SHDRRA6W100P 0X508_1X6_3240 X1200X860P | TERM BLOCK HDR 6POS 90DEG 5.08MM | 2 | Purchased |

| | | | | | | |
|---|---|---|---|---|---|---|
| U1, U2 | Load Balancing Board | Analog Devices | FP-MS8-8-05-08-1660-IPC_A | IC OR CTRLR N+1 8MSOP | 2 | Purchased |
| BATT RETAIN COIN | Leak Sensor | Digikey | BAT-HLD-005-THM | 1 CELL PC PIN | 1 | Purchased |
| LED RED CLEAR | Leak Sensor | Digikey | SMTL6-RC | 6PLCC SMD | 1 | Purchased |
| CONN HEADER VERT | Leak Sensor | Digikey | TSW-102-07-L-S | 2POS 2.54MM | 1 | Purchased |
| Resistor 1 | Leak Sensor | Digikey | KTR10EZPF1004 | SMD 1M OHM 1% 1/8W 0805 | 5 | Purchased |
| Resistor 2 | Leak Sensor | Digikey | ERJ-6ENF20R0V | SMD 20 OHM 1% 1/8W 0805 | 5 | Purchased |
| MOSFET 2P-CH, TSMT6 | Leak Sensor | Digikey | QS6J11TR | 12V 2A | | Purchased |
| Realsense Intel Depth Camera | Peripherals | Intel | D495/D495i | 90 mm x 25 mm x 25 mm | 2 | Purchased |
| Camera PCB | Peripherals | In-House | -- | -- | 2 | Custom |
| Hydrophones | Peripherals | Aquarian Audio | H2C | 25 x 58mm (1" x 2-1/4") | 4 | Purchased |
| Depth Sensor | Peripherals | Blue Robotics | MS5837-30BA | -- | 1 | Purchased |
| USB Hub | Peripherals | Amazon | HB-UM43 | 3.4 x 1.4 x 0.61 inches | 1 | Purchased |
| LED RED CLEAR | Peripherals | Digikey | 150080SS75000 | 0805 SMD | 3 | Purchased |
| LED BLUE CLEAR | Peripherals | Digikey | 150080BS75000 | 0805 SMD | 3 | Purchased |
| LED GREEN CLEAR | Peripherals | Digikey | 150080GS75000 | 0805 SMD | 3 | Purchased |
| LED YELLOW CLEAR | Peripherals | Digikey | 150080YS75000 | 0805 SMD | 3 | Purchased |
| LED WHITE CLEAR | Peripherals | Digikey | 150080WS75000 | 0805 SMD | 4 | Purchased |
| Capacitor 1 | Camera PCB | Digikey | GRM188R71C102KA01D | -- | 1 | Purchased |
| Resistor 1 | Camera PCB | Digikey | ERJ-6GEYJ563V | -- | 1 | Purchased |

| | | | | | | |
|---|---|---|---|---|---|---|
| USB A header | Camera PCB | Amazon | 15910080 | -- | 1 | Purchased |
| USB C plug | Camera PCB | Amazon | USB4151-GF-C | -- | 1 | Purchased |
| Picoscope | Acoustic Processing and Filtering | PicoTech | Picoscope 4824 | 80 MS/s | 1 | Purchased |
| Acoustics System PCB | Acoustic Processing and Filtering | In-House | -- | -- | 4 | Custom |
| 9V Batteries | Acoustic Processing and Filtering | Target | Generic | -- | 4 | Purchased |
| CAP CER U2J 0603 | Acoustics PCBs | Digikey | GRM1887U1H512JA01D | 5100PF 50V | 5 | Purchased |
| CAP CER C0G/NP0 0603 | Acoustics PCBs | Digikey | 0603N102F500CT | 1000PF 50V | 8 | Purchased |
| CAP CER X5R 0603 | Acoustics PCBs | Digikey | CL10A105KA8NNNC | 1UF 25V | 30 | Purchased |
| CAP CER X7R 0603 | Acoustics PCBs | Digikey | CL10B104KB8NNWC | 0.1UF 50V | 10 | Purchased |
| LED RED CLEAR | Acoustics PCBs | Digikey | 150080SS75000 | 0805 SMD | | Purchased |
| Resistor 1 | Acoustics PCBs | Digikey | RNCP0603FTD10K0 | 10K OHM 1% 1/8W 0603 | 6 | Purchased |
| Resistor 2 | Acoustics PCBs | Digikey | RNCP0603FTD1K00 | 1K OHM 1% 1/8W 0603 | 8 | Purchased |
| Resistor 3 | Acoustics PCBs | Digikey | ERJ-3EKF4701V | 4.7K OHM 1% 1/10W 0603 SMD | 10 | Purchased |
| Resistor 4 | Acoustics PCBs | Digikey | ERJ-3EKF5492V | 54.9K OHM 1% 1/10W 0603 SMD | 6 | Purchased |
| Resistor 5 | Acoustics PCBs | Digikey | RC0603FR-0741K2L | 41.2K OHM 1% 1/10W 0603 | 5 | Purchased |
| Resistor 6 | Acoustics PCBs | Digikey | ERJ-3EKF1742V | 17.4K OHM 1% 1/10W 0603 SMD | 6 | Purchased |

| | | | | | | |
|---|---|---|---|---|---|---|
| Resistor 7 | Acoustics PCBs | Digikey | ERJ-3EKF1302V | 13K OHM 1% 1/10W 0603 SMD | 1 | Purchased |
| Resistor 8 | Acoustics PCBs | Digikey | ERJ-3EKF6980V | 698 OHM 1% 1/10W 0603 SMD | 6 | Purchased |
| Resistor 9 | Acoustics PCBs | Digikey | ERJ-3EKF5360V | 536 OHM 1% 1/10W 0603 SMD | 6 | Purchased |
| Resistor 10 | Acoustics PCBs | Digikey | ERJ-3EKF1653V | 165K OHM 1% 1/10W 0603 SMD | 6 | Purchased |
| Resistor 11 | Acoustics PCBs | Digikey | ERJ-3EKF8662V | 86.6K OHM 1% 1/10W 0603 SMD | 5 | Purchased |
| Resistor 12 | Acoustics PCBs | Digikey | ERJ-3EKF1102V | 11K OHM 1% 1/10W 0603 SMD | 6 | Purchased |
| Resistor 13 | Acoustics PCBs | Digikey | ERJ-3EKF5761V | 5.76K OHM 1% 1/10W 0603 SMD | 5 | Purchased |
| Resistor 14 | Acoustics PCBs | Digikey | ERJ-3EKF3320V | 332 OHM 1% 1/10W 0603 SMD | 5 | Purchased |
| Resistor 15 | Acoustics PCBs | Digikey | ERJ-3EKF1740V | 174 OHM 1% 1/10W 0603 SMD | 8 | Purchased |
| Resistor 16 | Acoustics PCBs | Digikey | RMCF0603ZT0R00 | 0 OHM JUMPER 1/10W 0603 | 6 | Purchased |
| Resistor 17 | Acoustics PCBs | Digikey | ERJ-3EKF3000V | 300 OHM 1% 1/10W 0603 SMD | 5 | Purchased |
| SWITCH SLIDE DIP SPST | Acoustics PCBs | Digikey | 416131160803 | 25MA 24V | 1 | Purchased |
| IC AUDIO 4 CIRCUIT 14TSSOP | Acoustics PCBs | Digikey | OPA1604AIPWR | 40V 10mA (-0.5 to +0.5 V) | 1 | Purchased |

| | | | | | | |
|---|---|---|---|---|---|---|
| IC OPAMP PGA 1 CIRCUIT TSOT23-8 | Acoustics PCBs | Digikey | LTC6910-3CTS8#TRMPBF | 11V 25mA | 1 | Purchased |
| CONN RCPT 2POS IDC 22AWG TIN | Internal Connectors | Digikey | 3-640440-2 | 22 AWG | 1 | Purchased |
| JUMPER W/TEST PNT | Acoustics PCBs | Digikey | 60900213421 | 1X2PINS 2.54MM | 1 | Purchased |
| Voltage References Rail Virtual Ground | Acoustics PCBs | Mouser | TLE2426CDG4 | 2 V to 20 V/20mA | 1 | Purchased |
| Thruster Mounts | Mounts and 3D printed components | In-house | -- | -- | 8 | Custom |
| Endcap Interface | Mounts and 3D printed components | In-house | -- | -- | 1 | Custom |
| Camera Enclosure Mount | Mounts and 3D printed components | In-house | -- | -- | 2 | Custom |
| Angle Brackets | Mounts and 3D printed components | In-house | -- | -- | 16 | Custom |
| Frame Joints | Mounts and 3D printed components | In-house | -- | -- | 16 | Custom |
| Hinges | Mounts and 3D printed components | McMaster-Carr | -- | -- | 4 | Purchased and Customized |
| Latch and Lock | Mounts and 3D printed components | McMaster-Carr | -- | -- | 2 | Purchased and Customized |
| Threaded Rod Caps | Mounts and 3D printed components | In-House | -- | -- | 8 | Custom |
| Red Powerpoles | Internal Connectors | Powerwerx | 1327 | For 15, 30, 45 amp contacts | 31 | Purchased |

| | | | | | | |
|---|---|---|---|---|---|---|
| Black Powerpoles | Internal Connectors | Powerwerx | 1327G6 | For 15, 30, 45 amp contacts | 31 | Purchased |
| Blue Powerpoles | Internal Connectors | Powerwerx | 1327G8 | For 15, 30, 45 amp contacts | 16 | Purchased |
| White Powerpoles | Internal Connectors | Powerwerx | 1327G7 | For 15, 30, 45 amp contacts | 16 | Purchased |
| Green Powerpoles | Internal Connectors | Powerwerx | 1327G5 | For 15, 30, 45 amp contacts | 18 | Purchased |
| XT90 | Internal Connectors | Amazon | 1728 | 5mm gold bullet connector in nylon shroud 90 A | 2 | Purchased |
| XT90-S | Internal Connectors | Amazon | 1728 | 5mm gold bullet connector in nylon shroud 90 A | 2 | Purchased |
| XT60 | Internal Connectors | Amazon | -- | -- | 1 | Purchased |
| XT60-S | Internal Connectors | Amazon | -- | -- | 1 | Purchased |
| Duponts | Internal Connectors | Amazon | -- | -- | -- | Purchased |
| CONN RCPT 2POS IDC 22AWG TIN | Internal Connectors | Digikey | 3-640440-2 | 22 AWG | 32 | Purchased |
| Ring Terminal Connector 1 | Internal Connectors | Amazon | -- | -- | 4 | Purchased |
| Ring Terminal Connector 2 | Internal Connectors | Amazon | -- | -- | 16 | Purchased |
| Ring Terminal Connector 3 | Internal Connectors | Amazon | -- | -- | 2 | Purchased |
| WetLink Penetrators | External Connectors | Blue Robotics | WLP-M10-6.5MM-LC | 6.5 mm +- 0.3mm cable diameter (7075-T6 Aluminum, Anodized) | | Purchased |
| Potted Cable Penetrators | External Connectors | Blue Robotics | PENETRATOR-M-BOLT-8MM-10-25-R2-RP | M10 thread, for 8mm cable (Aluminum 6061-T6) | 2 | Purchased |

| | | | | | | |
|---|---|---|---|---|---|---|
| Tether Plug | External Connectors | Fischer | S 104 A066-130+ | -- | 2 | Purchased |
| Tether Receptacle | External Connectors | Fischer | DEU 104 A066-130 | -- | 2 | Purchased |
| Tether Clamp | External Connectors | Fischer | E3 104.2/7.7 + B \| SE | -- | 2 | Purchased |
| Camera Plug | External Connectors | Fischer | S 104 A056-130+ | -- | 2 | Purchased |
| Camera Receptacle | External Connectors | Fischer | DEU 104 A056-130 | -- | 2 | Purchased |
| Camera Clamp | External Connectors | Fischer | E3 104.2/7.7 + B \| SE | -- | 2 | Purchased |
| Hydrophone Plug | External Connectors | Fischer | S 103 A051-130+ | -- | 4 | Purchased |
| Hydrophone Receptacle | External Connectors | Fischer | DEU 103 A051-130 | -- | 4 | Purchased |
| Hydrophone Clamp | External Connectors | Fischer | E31 103.2/5.7 + B \| SE | -- | 4 | Purchased |
| Kill Switch Plug | External Connectors | Fischer | S 103 A051-130+ | -- | 1 | Purchased |
| Kill Switch Receptacle | External Connectors | Fischer | DEU 103 A051-130 | -- | 1 | Purchased |
| Kill Switch Clamp | External Connectors | Fischer | E31 103.2/5.7 + B \| SE | -- | 1 | Purchased |
| Thruster Plug | External Connectors | Fischer | S 104 A040-80+ | -- | 8 | Purchased |
| Thruster Receptacle | External Connectors | Fischer | DEE 104 A040-80 | -- | 8 | Purchased |
| Thruster Clamp | External Connectors | Fischer | E3 104.2/6.7 + B \| SE | -- | 8 | Purchased |
| Battery Plug | External Connectors | Fischer | S 105 A087-130+ | -- | 2 | Purchased |
| Battery Receptacle | External Connectors | Fischer | DEU 105 A087-130 | -- | 2 | Purchased |
| Battery Clamp | External Connectors | Fischer | E31 105.2/10.0 + B \| SE | -- | 2 | Purchased |
| Expansion Plug | External Connectors | Fischer | S 104 A037-130+ | -- | 1 | Purchased |
| Expansion Receptacle | External Connectors | Fischer | DEU 104 A037-130 | -- | 1 | Purchased |

| | | | | | | |
|---|---|---|---|---|---|---|
| Expansion Clamp | External Connectors | Fischer | E3 104.2/7.7 + B \| SE | -- | 1 | Purchased |
| Fischer receptacles for acoustics | External Connectors | Fischer | DEU 103 A051-130 | -- | 4 | Purchased |
| Fischer receptacle caps | External Connectors | Fischer | 48 103.2273 Recpt cap, Chrome plated | -- | 4 | Purchased |
| Caps | External Connectors | Fischer | 104.714 \| Cap D | -- | 2 | Purchased |
| Caps | External Connectors | Fischer | 103.2273 Recpt cap, Chrome plated | -- | 2 | Purchased |
| Waterproof Cable Splicer | External Connectors | ELifeApply | RoHS IP68 | 83mm | 4 | Purchased |
| Fischer O-rings | External Connectors | Fischer | -- | 0.63 in diameter | 16 | Purchased |
| Penetrator O-rings | External Connectors | Blue Robotics | -- | 0.63 in diameter | 6 | Purchased |
| Camera Cables | Cables | Igus | AWM Style 20233 VW-1 | 100 Ohm Single Pair Ethernet RoHS-II | 2 | Purchased |
| Killswitch Cable | Cables | Igus | AWM Style 2464/2576 | 20 AWG | 1 | Purchased |
| Battery Cables | Cables | Igus | AWM Style 20317 | 300V RoHS Conform | 2 | Purchased |
| System switch cable | Cables | Igus | -- | -- | 1 | Purchased |

Figure 25: Component Specifications