RoboSub Team Killick

Mid-project Report
Fall Semester 2016

-Full report -

by
Brett Gonzales
Tyler Loughrey
Nate Marquez
Chris McLean
Phil Meister
Seth Purkey
Mitchell Yohanan

Department of Electrical and Computer Engineering
Colorado State University
Fort Collins, Colorado 80523

Project advisor(s): Dr. Anthony Maciejewski
Megan Emmons
Chris Robbiano

Approved by: Megan Emmons and Chris Robbiano

Abstract

Mechanical

The mechanical sub-team is responsible for designing, manufacturing, and testing the mechanical components of the vessel. The three main mechanical components include the chassis, electrical housing, and the fail safe system. Some major considerations that were evaluated include the thermodynamics of the housing, the buoyancy of the vessel, the drag and pressure forces on the vessel, and the materials to choose for the components.

The RoboSub competition rules state that the maximum dimensions of the vessel may not exceed 6’x3’x3’. The maximum weight may not exceed 125 lbs. The rules also state that the vessel must be positively buoyant upon electrical failure. The mechanical team has also decided on personal team constraints for the vessel. The materials in contact with the water must be corrosion resistant. Also, the prototype vessel will have a transparent housing for our cameras to see out of and also for us to see visual indicators on the inside of the housing during run time. In order to mitigate risk, the mechanical team decided to set the constraint of compartmentalization of electrical components in the housing. The mechanical sub-team had to take these constraints into consideration when designing the vessel.

During the Fall 2016 semester, the mechanical team was dedicated to designing the three main mechanical components of the vessel. This was done through the use of statistical analysis, simulations in computational fluid dynamic software, industry design reviews, CAD modeling, and use of fluid and material computations.

During the Spring 2017 semester, the mechanical team will be focusing on purchasing of components, manufacturing of the vessel, testing, and necessary redesign. The mechanical team will be working closely with industry and team partners in manufacturing of the vessel.

Sensors

The Sensors sub-team’s focus is to visualize the world around the sub through the use of our measured data. The sensors sub-team is the “eyes” of the project, and is in charge of determining the location and movement decisions of the vessel.

Once the sensors take raw data, such as inertial movement data, voltage readings of pressure, and images, the sensors then send this data to the processing units for refinement and movement decisions.

The goal of the sensors sub-team is to develop a movement decision subsystem for the vessel. For the Fall 2016 semester, the teams focus was on developing an understanding of coding and how to read the data given by the sensors. The team also focused on researching different sensors and processors that would fit the vessel’s needs, and testing

out different filtering schemes for simulated data. During the Spring 2017 semester, the sensors sub-team plans on collecting real-world sensor data. This data will then use to adjust programs from simulations, test for hardware risks, and develop a basic navigation system which can be easily expanded upon by future teams

Propulsion

Power and Propulsion sub-team is vested in control, feedback, and powering of all systems throughout the vehicle. Subsystems directly under design by the sub-team are motors, motor processing, inertial feedback control, motor driving, and power supply.

The RoboSub rules provide very loose constraints on the electrical characteristics permitted during the competition. The majority of constraints are sub-team generated on the basis of time and cost: any device or system that decreases learning or development time while constituting a minimal impact for evaluation is highly desired.

The Fall 2016 semester was dedicated to the prototype phase of the vehicle. It is the focus of the sub-team to design, test, and implement two brushless DC motors, one real-time motor processing unit, software-based feedback on the main control unit from the sensors sub-team, a simplified motor driver in the form of an electronic speed controller, as well as management and usage of LiPo battery technology. The simplification of the motor driver to an electronic speed controller removes the requirement that the sub-team build and implement a multi-phase synchronous motor driver, which is extremely time intensive and costly.

The Spring 2017 semester is dedicated to final testing, refinement, and understanding of the prototype vehicle. Once the prototype phase is fully vetted, it is the goal of the power and propulsion sub-team to increase the size of the pertinent subsystems to a full vehicle scale: 6 brushless DC motors, 6 electronic speed controllers, and possible addition of a LiPo battery for increased scale. This will require extra design considerations as well as testing time to account for full-sized vehicle dynamics.

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Chapter 1 – Introduction

The RoboSub team is an evolutionary senior design project at CSU in designing, implementing, testing, and competing with an autonomous underwater vehicle (AUV) in cooperation with the United States Navy RoboSub competition. Team Killick is the first team at CSU to establish a foundation for future RoboSub teams.

Three electrical engineering (EE) undergraduates, two electrical engineering graduates, one computer engineering (CE) undergraduate, and three mechanical engineering (ME) undergraduates form the core senior design team with OOP underclassmen (EE/CE) forming the continuing basis for future senior design members. The estimated budget for this project is $11700. The rules will be released for the 2016-2017 competition year in December 2016, with the competition commencing in June 2017.

This project has three aspects: motors/controls, sensing/processing, and mechanical. Two EE's are focusing on construction, implementation, and testing of motors and controls while one EE and one CE are focusing on the image processing and sensing necessary for navigation. The three ME's focus is on design, implementation, and testing of vehicle exoskeleton, propulsion requirements, and overall water suitability of the vehicle.

Success in the competition is measured on course completion, event duration, and overall design. Overall design consists of: technical merit, craftsmanship, safety, website design, team coherence (attire and technical vehicle knowledge), and documentation. Event duration consists of completing prescribed courses (comprised of tasks in a systematic order) in the shortest amount of time. The RoboSub rules dictate all static and dynamic event scores, as well as the specific event criteria. Rewards are paid according to position standing, and contribute to any future teams' available funding.

As per the rules and regulations of the 2016 RoboSub Competition, the following has been considered in the design of each aspect of Team Killick's vessel. The vessel needs to be able to follow an orange guide that leads to each obstacle. The buoy obstacle needs to identify the color of each buoy and touch them in the correct order. The PVC pass over obstacle consists of passing through a "portal" with extra points awarded to "style". The Bins obstacle will remove a "lid" from a "bin" and place markers into this "bin". The firing torpedoes obstacle will have targets that need to be fired at in a correct order. The object recovery and octagon obstacle will use an acoustic pinger that indicates the location of the objects that need to be placed in a certain area to receive maximum points. These obstacles may be modified for the 2017 competition.

Further design constraints have been implemented by the competition rules and other design considerations. The competition implements several strict outlines of what is allowed. The weight of each vessel is eligible for additional points if the vehicle is under 84 pounds. There is also a penalty for any vessel over 84 pounds with a maximum weight of less than 125 pounds. Any vessel over 125 pounds will be disqualified. The size of each vessel must fit inside a 3 foot by 3 foot by 6 foot box, any vessel over this size will not be able to compete. Each vessel must have markers that fit into a box that is 2 inches by 6 inches long and weigh less than 2 pounds each. The torpedoes have the same requirements as the markers and cannot exceed a speed that causes a bruise when striking a person. These are the main regulations that have constrained the design of CSU's AUV. These rules can be found in last year's competition official website [1P].

Constraints of safety, vessel life, and manufacturability have been included by each member of team Killick during the design process. Safety of the vessel has been aimed to minimize the worst case scenarios that may inflict harm to users or the environment. Vessel life will be maximized with the use of corrosion resistant materials that can withstand the expected abuse over the course of its lifetime. The manufacturability of the vessel is constrained by the resources available to the team. With the use of a simple design and the clever selection of materials the team can meet the given constraints and stay within the team's budget.

This first year design is not directed at winning the competition, but rather to establish a simple and functional vehicle for future iterations to expand upon. The 2016-2017 senior design team is anticipating completion of the vessel structure, propulsion, and navigation controls with a budget of $11,700. Structure consists of an exoskeleton with proper supports and a waterproof enclosure for the electrical equipment. Propulsion consists of low voltage, medium amperage out-rigger motors powered by a DC source. Navigation consists of optical devices, as well as inertial sensors.

With Team Killick being the inaugurating team for CSU, the first iteration is largely based off of collaboration between team members and reverse engineering of past projects. By analyzing the components used on past projects, a comparable prototype was designed. CSU's Team Killick has high hopes for the first iteration of the vessel.

Chapter 2 – History of Previous Work

Autonomous Underwater Vehicles are becoming more popular as unmanned vehicles advance with technology. Initially, the use of AUV's was utilized for commercial use. For example, oil companies used these unmanned vehicles to accomplish cheap geographical mapping of the ocean floor. Now AUV's have found a spot in military and consumer applications. Military applications include scouting, mine countermeasures, delivery, and oceanography. Personal use has become popular by exploring marine life. This application is fantastic as it gives users the ability to see and experience locations that were before unreachable or too dangerous to venture into.

The US Navy hosts a competition yearly to promote the expansion and ingenuity of what can be achieved with AUV's. The basis of the completion is to navigate an underwater course made up of obstacles and different objectives including path following, inertial navigation, identifying objects of interest, precision shooting of torpedoes, and accurate control of buoyant forces. Different teams from across the world bring their AUV's to compete. Each year, teams push the boundaries of how fast these objectives can be completed. Teams from Universities such as Cornell and Florida State have been competing in this event for the past fifteen years and are continually top competitors in the competition. Even though this is the first year that CSU is considering the competition, we expect to be amongst this group in the future.

Chapter 3 – Budget and Fundraising

The budget was created by researching past and current RoboSub team's journal papers. The parts listed in these papers were collected and used to create the estimated budget as seen in Appendix B Figure 8. A more detailed breakdown follows the table based on the estimated allotments per category.

The team has been successful in meeting and exceeding the estimated budget through sponsorships. Originally the team started out with $1,400 from the CSU ECE Department. Since then, the team has successfully raised an additional $15,200 through sponsorships from Ball Aerospace, Hewlett Packard, and IEEE. This brought the grand total of money raised to $16,600, which gave us a good amount of reserve funds.

No money has been spent yet due to a delay in acquiring a Procurement card from Colorado State University. This problem is now resolved and the team is planning on purchasing and acquiring a majority of the needed material in the next two weeks. The bill of materials is currently under the final revision and upon the approval, the purchasing process will proceed.

Chapter 4 – Mechanical Sub-team

Chassis

Objectives and Constraints

The purpose of the chassis is to provide protection and modular placement. Along with these main objectives there are constraints that tie in with this. The rules of the RoboSub competition restrict the size and weight of the entire vessel to be less than a 3' by 3' by 6' box and less than 125 pounds. Another constraint that has been decided on is the material to be used. The material has to be corrosion resistant to operate in an aquatic environment. The material also will be a t-slotted extrusion for this first year. The reason a t-slotted extrusion will be used is to provide modular placement for any design changes that occur. This is important since this is the first year that CSU has had a RoboSub team.

Alternative Design Processes

The current design of the chassis had several considerations. However, the current box design was originally put into a decision matrix to narrow down the considerations for an optimal design. The importance was agreed on and the results were ranked from 1-5, with 5 being the best. The scores from each mechanical team member was averaged and the results are shown in Appendix E.

The decision matrix led the team to consider the sled, box, and x-wing designs as the top designs. The next decision that was decided on was the material to use for the chassis. The chassis has to be corrosion resistant, strong, and provide a modular frame for the motor placement. The t-slotted aluminum extrusion was decided on since it filled the requirements for the material needed. With the top designs decided on, the mechanical team started to CAD up some basic designs. While the sled design took the top spot of the decision matrix, the mechanical team decided not to continue considering this design due to limited motor placement/protection. The box and x-wing design are shown in the Figure 1 below.

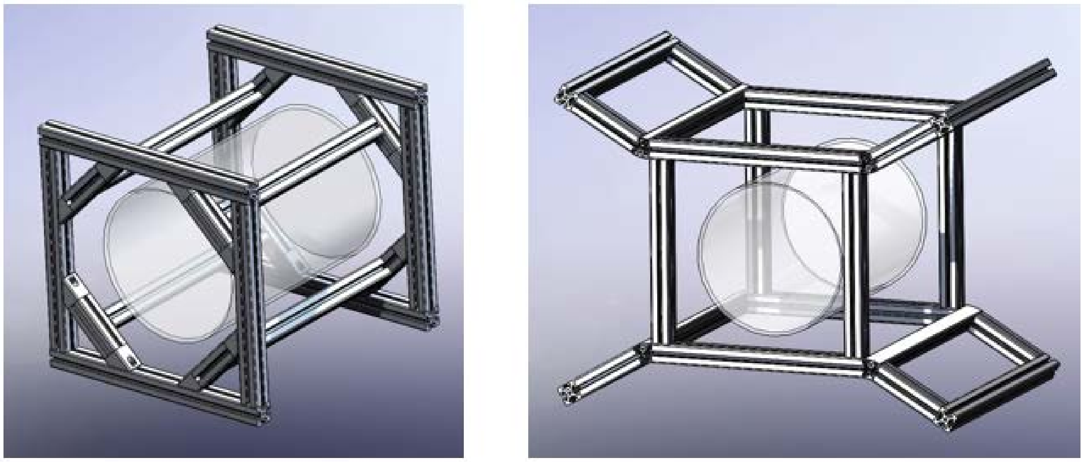


Figure 1– Box (Left) and X-wing (Right)

The x-wing design had unnecessary “wings” that were not structurally sound and awkward. This led to the x-wing design to be abandoned and the box became the primary chassis design. The box was improved several times until the current design as shown in Figure 2 below.

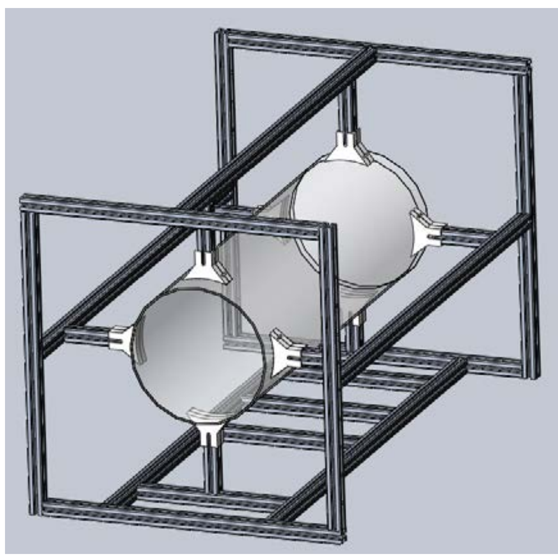


Figure 2– Current Prototype Chassis Design

Testing

The chassis is designed to survive an aquatic environment, however with limited resources tests need to be designed and implemented to test different aspects of the chassis. The tests that the mechanical team have decided to run are as follows: fatigue, impact, corrosion, and dry-land loading. The fatigue test will determine if the chassis will maintain its original shape after multiple simulated crashes. The impact test is will determine that the chassis can maintain structural rigidity while experiencing an impact. This impact force will equate to a collision happening while the vessel is traveling at maximum velocity. The corrosion test will place a piece of the chassis in salt water, fresh water, and chlorinated water over an extended period of time to see the effects. The dry-land loading test will insure that the chassis can hold the electronic housing at different angles. For further testing descriptions please see Appendix H for the full testing procedures.

Risk Mitigation

The chassis needs to mitigate the risk involved with potential failures. The two main functions of the chassis are the protection of the vessel and mounting the motors. A FMEA was used in order to address the potential failures and what corrective action will be used to minimize the consequences of such failures. This FMEA can be found in Appendix D.

Electrical Housing

Objectives and Constraints

The purpose of the electrical housing is to maintain an ideal environment for the electrical components being housed inside. The housing holds the batteries, sensors, cameras, and processing units necessary for the vessel to autonomously navigate. Some major considerations in the design of the housing include the seal design, buoyancy, heat dissipation, compartmentalizing of components, ease of access, and strength. These are further elaborated on in the following sections and explained how the final design was concluded.

Alternative Design Processes

The first step in the design of the electrical housing was deciding on an overall shape of the housing. We did this by brainstorming numerous shapes of the housing and narrowing down our decision to three final designs from a decision matrix. Refer to Appendix E, Figure 2M, for the electrical housing decision matrix. The three final designs that were concluded from the decision matrix were the half-capsule, full-cylinder, and semi-sphere. After researching manufacturing costs, we found that the semi-sphere was unreasonable and decided to include the half cylinder in our final three concepts for the electrical housing.

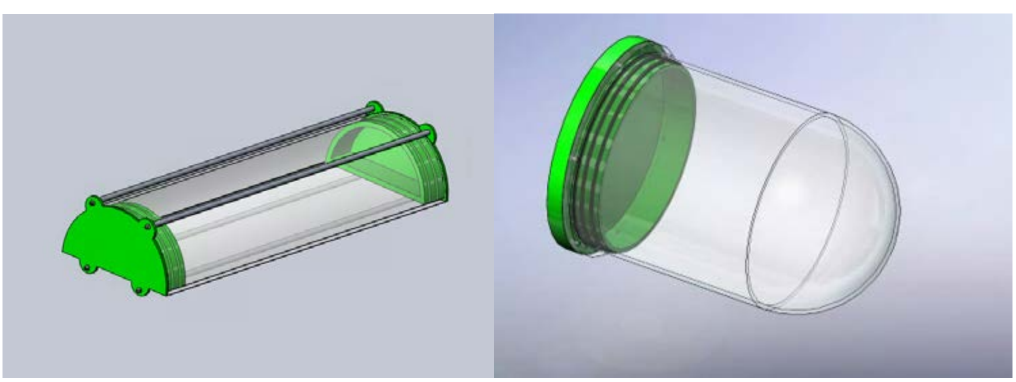


Figure 3- half cylinder *Figure 4- half capsule*

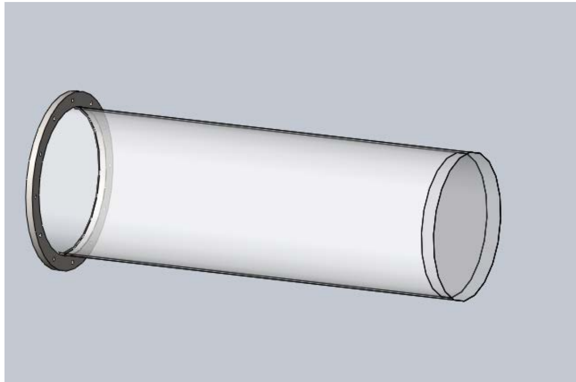


Figure 5- full cylinder

Upon further discussion and research of the three potential designs, we finalized our decision to be the full cylinder. The reason for this was due to ease of manufacturability because a cylinder is a common structure that can be manufactured in various materials. Another reason for this decision was due to ease of sealing. An O-ring seal design for the end cap of the housing is very common and would not be able to be implemented with a half-capsule or semi-sphere design.

After finalizing the shape of the housing, the overall dimensions had to be finalized. The positive buoyancy generated from the housing was another major design consideration that was used to determine the size of the housing. This limited the size of the housing and overall dry land weight of the vessel. The upward buoyancy of an object in water is dependent upon the volume of the object and the dry land weight of the vessel that offsets the upward buoyant force. The vessel needs to be neutrally buoyant in water to allow the motors to easily navigate to different depths without the vessel naturally rising or falling.

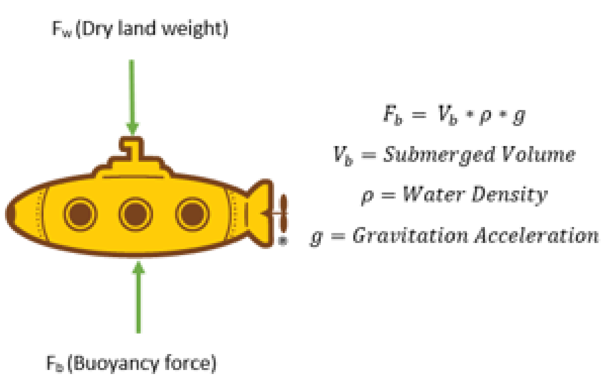


Figure 6- Buoyancy Equation

Since the positive buoyancy must be offset by the dry land weight to achieve neutral buoyancy, the size of the housing will set our overall weight. The weight of the vessel has to be less than 125 lbs as constrained by the competition rules. Refer to Figure 3M in Appendix E for the table that summarizes various dimensions of the electrical housing cylinder along with the required dry land weight.

The final design that we decided on was a 10” diameter, 31” long cylinder which sets our weight at 95 lbs. We finalized our design at these dimensions because it gives us a weight that is less than 125 lbs while giving the vessel able amount of volume to hold electrical components inside. We estimated our electrical components to take up an area of ~3ft x 1ft.

Another major consideration for the housing is the material which to manufacture it out of. The electrical housing material needs to be corrosion resistant and transparent to allow the cameras to see out of. It also needs to be transparent in order for us to see visual indicators during testing. This limited us to three materials to choose from: acrylic, clear PVC, and polycarbonate. We finalized our decision to be clear PVC due to it having a high fracture toughness and yield strength and it’s also a lot cheaper than polycarbonate.

Another alternative to the clear PVC tube that was researched was using a corrosion resistant 440C stainless steel to maximize heat transfer. We could incorporate a clear window for the cameras in this design. A material selection process was done using the CES software with the following performance indices and constraints to find this material.

- Constraints: shape=tube
- Fracture toughness>23 ksi*in^2
- Corrosion resistance in water = Excellent
- Minimize cost performance index (PI 1)
- Maximize heat transfer performance index (PI 2)

Refer to Appendix E, Figures 4M & 5M, for the CES generated graphs which were used to select a material which satisfies the performance indices which minimize cost, and maximize heat transfer. For the test rig, we will be using a clear PVC housing due to the low cost and we will use stainless steel 440C if heat becomes an issue from testing.

The housing also needs to be able to maintain a low enough temperature in order for our sensors and electrical components to operate correctly. Due to this, we need to use a thermally conductive material to allow heat to be transferred to the outside of the housing. We decided on using a high conductivity metal as the end cap of the housing to assist in this function.

This design was modeled in CFD software Fluent to measure the heat rate through the housing with different end cap designs, thicknesses, and materials as well as different fan placements. The Fluent temperature and vector plot can be viewed in Appendix E Figure 6M & 7M. The results of this simulation showed that an aluminum end cap resulted in 88 W more of total heat transfer compared to a clear polymer. It also showed that adding fins to the end cap significantly increased the heat transfer by 100 W. A surface plot was generated in Minitab to compare a stainless steel cap to an aluminum cap. Each material was also compared with no fins and fins. This is shown in Appendix E Figure 8M. Using this data, we decided to use a 6061 aluminum end cap with fins and also incorporate two fans into the housing.

Figure 7- Aluminum end cap

One of the major functions of the housing is to maintain a dry environment for the internal electrical components. To seal the housing, one side will be a permanent clear PVC window for the front facing camera. The other aluminum end cap will contain two O-rings for sealing and 6 water proof connectors for motor wires to leave the housing. This design was reviewed and validated by industry partners.

Due to the electrical team having the need to easily access and modify components, the housing will incorporate two retractable drawers mounted on A36 steel circular brackets. Refer to Appendix E Figure 9M to view the housing drawer design. The brackets will be mounted in the housing on 3D printed PLA sliders to allow easy adjustment of the brackets to change the center of gravity of the vessel if needed. Refer to Appendix E for an image of the 3D printed bracket slides

The housing will be mounted to the chassis using eight 3D printed ABS plastic mounts. These clamps will fit over the 80-20 chassis and have a slit in them to allow a hose clamp to fit in them. This pulls the clamps tightly against the housing to ensure that it is secure. Refer to Appendix E Figure 10M & 11M for images of the clamps.

A full CAD image of the electrical housing incorporated with the chassis is available in Appendix E Figure 13M.

Testing

Two major tests will be conducted on the electrical housing to validate the design: a water proof timed test, and a heat dissipation test. Refer to Appendix H for a more in depth description of these tests.

Risk Mitigation

Some of the major failure modes of the electrical housing will be from seals leaking and condensation (refer to Appendix D). We plan to mitigate the risk of seals leaking by following all the guidelines listed in the parker handbook [1] as well rating our O-rings for at least 2X safety factor of pressure at max depth. We will include a redundancy of 2 O-rings on the cap as well to mitigate this. We will have a water sensor in the housing to initiate the fail safe if much condensation is detected.

Fail Safe

Objectives and Constraints

Upon electrical failure it is required, per the rules of the competition, for the vessel to have .5% positive buoyancy. Because we are not using a ballast system that manipulates the weight of the vessel with an intake of water, we had to implement a ballast that's sole purpose is to achieve a small amount of positive buoyancy. A major focus is that the ballast must be highly reliable, simple, and effective.

Alternative Design Processes

The initial fail safe was to be incorporated with the bladder like ballast system. An example of this can be seen in Appendix E, Figure 12M. These designs included a high pressure pump design that would release upon failure. The designs included a single high pressure pump and a water and air dual pump system. The other potential designs were mass ejection and a piston design. Mass ejection was the process of releasing a large amount of air from a compressed tank, but upon calculating the needed amount of CO2 required the design was quickly tossed out. The piston design utilized the idea of using compressed air to push a piston open and in turn increasing the volume of the vessel. This idea along with the pump designs were eventually scrapped due to the decision that the amount of moving parts and complexity of each of the system highly affected the reliability of the fail safe. The design of simply inflating a bladder with compressed air to increase the vessels volume displacement was then decided on. This system requires only three components: a CO2 cartridge, a normally opened solenoid valve, and a malleable, balloon like, material that can withstand the underwater pressure of a max depth of 40 feet. With a safety factor of 2, that max pressure is to be rated to 34.68psi.

Testing

The fail safe needs to have an extremely high reliability factor. Due to this, each component along with a fully assembled system will be extensively tested. The first test is to assure the normally open valve actuates upon electrical signal loss. Once this test is completed the CO2 cartridge can be attached to the valve and then the test can be repeated to ensure the air is properly ejected. Finally, with the air tight attachment of the bladder, the inflation can be tested for volume displacement and leaks. Each of these tests will be ran through many iterations to ensure reliability. For further reference, see section H in the Appendix.

Risk Mitigation

Potential risks with the fail safe system is failure to properly inflate the bladder. The bladder could potential get caught within the enclosure as well as potentially tear. Precautions to make these effects not occur are using material rated to max pressures put out by the CO2 cartridge as well as making all surfaces smooth and internally lubricated so sticking will not occur. Please reference Appendix D for more details.

Fluid Dynamics

Objectives and Constraints

The movement of the vessel through water is directly correlated to the thrust provided by the externally mounted motors. Due to the high viscosity of water, compared to that of air, the movement of the vessel through water causes a high drag coefficient and in turn large drag force. Other constraints that affect the movement of the vessel through water are the shape and weight. The more aerodynamic the shape of the vessel, the lower the drag coefficient is. Weight affects the inertial movement required to initially and continually move the vessel. The constraints the help determine the force required to move the vessel at a certain speed. With a known force, the correct motor can be properly picked to ensure proper propulsion.

Alternative Design Processes

To determine the forces acting upon the vessel while moving, certain variable had to be assumed to run CFD analysis. We were able to find the known values for the surface area, maximum velocity, and time. Through the use of fluent the mechanical team was able to determine the drag coefficient for vessel, 1.418. The overall thrust forces required to move the vessel was then calculated at different accelerations compared shown in Appendix E Figure 14M.

This process was for finding the forward movement of the vessel. Because of the change in surface area during lateral movement, different thrust is required to reach the same accelerations. Upon calculating the forces for forward and lateral movements, the thrust needed was found to be 11.84lb-f and 22.034lb-f respectively.

Testing

This data gives the propulsion team a good idea of what the motors need to be rated to. The testing will consist of in water tests to determine if the thrust required at max velocity is close to that of our calculations. Because this data was found using CFD analysis, it is a great approximation of what forces may exist on the vessel, but not perfect.

Chapter 5 – Sensors Sub-team

Hardware

Optical Devices

Objectives and Constraints

Optical devices are to be added to the final vehicle as a main means of navigation. The optical device chosen in this case is a single camera, used to track a guiding line along the bottom of the obstacle course containing pool. The goal of this single camera is to be able to correctly identify the guiding line and be able to tell the position of the vehicle relative to the line, which will in turn tell the motor controllers how we need to maneuver the vehicle in order to stay on the track of the line.

For constraints, the camera hardware needs to satisfy the following requirements:

- At least 800x600 resolution
- At least 30 frames per second
- Under 3 Watts power consumption
- Under 1-pound weight
- Able to retrieve raw images from I/O with no need to pre-filter

Alternative Design Processes

No alternative options were considered other than cameras, as they are the most reliable and easiest devices to use for this task. The initial design of the optical system hardware was to use two cameras: one for line tracking, and one for obstacle detection. This plan changed to a single camera only for line tracking because of a consensus among the sensors sub-team, in which we decided that we do not need an additional camera as we will be only performing basic navigation with no intentionally placed obstacles as of this year.

Testing

For hardware testing, no such tests have been performed with the camera we want to use, as we have had difficulties in purchasing products as of this point. Before the semester ends we plan on ordering the camera, and testing of this camera will begin during the winter break. These tests will include power consumption tests and live-stream image capturing tests to see if raw images can be correctly pulled from the camera.

Risk Mitigation

The only risk that would be mitigated is if the camera simply does not work, in which case it will be returned for a refund, and a new camera will be purchased.

Inertial Devices

Objective and Constraints

The hardware constraints for the Inertial Measurement Unit (IMU) are a trade-off between accuracy and cost. The IMU will produce a negligible amount of heat. The IMU needs to have 9 degrees of freedom (DOF), with an accelerometer, gyroscope, and magnetometer in each orthogonal axis.

Many high-end IMU's have their own filtering for noise-reduction, and is desired to increase the accuracy from the IMU. Additional filtering to reduce noise further will be required. The IMU must be able to communicate over either a serial GPIO connection or USB to our SPU.

Alternative Design Processes

Alternate designs for an IMU have not been considered, as it is the best method of determining position. Some IMU's include an extra DOF as a pressure sensor, however we decided it would be best to use pressure transducers to track our depth in the water.

Testing

No hardware testing has been done of the IMU, as it has not been acquired yet. The IMU will be tested to confirm it can communicate with our SPU, and characterize the noise to confirm it is within the specification.

Risk Mitigation

The only risk with the IMU would be that it begins to return incorrect or extremely noisy signals. To reduce this, filtering must be coded so that outliers and noise are removed or reduced regardless of on-board noise reduction.

Pressure Transducers

Objective and Constraints

The pressure transducers need to be able to withstand a large amount of pressure, as deep underwater pressure can increase rapidly. The pressure transducers also need to be able to communicate with our SPU. This means that the SPU needs to be able to realize different voltages and relate them to the current underwater depth.

Alternative Design Processes

An alternate design for the pressure transducers would be to have it contained on the IMU as an extra DOF, however since the IMU is within the sub's electrical housing, it will not experience a relative amount of pressure.

Testing

No hardware testing has been done yet with the pressure transducers, but will need to be tested for correct output voltages as well as calibration.

Risk Mitigation

The biggest risk with the pressure transducers would be reporting an incorrect depth, making the sub think that we are deeper than we actually are. To mitigate this, the sub would need to be surfaced to fix the issue. The pressure transducers are waterproof, however if they break or fail, the sub will have no input from the transducers and would need to rely on the IMU to determine depth based on movement.

Sensor Processing Unit

Objective and Constraints

The hardware objective of the sensor processing units (SPU) is to be a programmable system that handles raw sensor data and converts it to navigation data.

For hardware, the SPU needs to have a fast enough processor to be able to handle incoming sensor data and output navigation data within a reasonable amount of time (about 300ms max). It also needs to be able to handle inputs from multiple I/O interfaces, as the Inertial Devices, Image Processing Unit, and Pressure Transducers do not all use the same I/O protocols. The SPU must also weigh within 1-2 pounds, and consume a minimal amount of power.

Alternative Design Processes

There were many options considered to fulfill this role. Initially, a miniature windows-capable PC was the choice of the SPU, but after reviewing specifications, specifically power consumption, this was found to be a poor choice. We have since chosen a single Banana Pi mini-computer to handle the data and convert it into a navigation decision.

Testing

No hardware testing of the SPU has been done as of this point, as we have been unable to purchase the Banana Pi. The SPU will be tested for hardware compatibility over Winter break. These tests will include I/O testing, as well as speed and power consumption tests.

Risk Mitigation

Hardware issues with the SPU could be that it fails to retrieve or transmit data from its I/O ports, failure to boot, or failure to meet processing speed requirements. To mitigate these, the SPU will be tested for I/O and boot functionality before being submerged and will have an error LED to alert if no input is being received from any of the sensors, the SPU will have a boot indicator LED, and finally the SPU will be replaced if it is not able to handle the data it is given.

Image Processing Unit

Objective and Constraints

The goal of the Image Processing Unit (IPU) is to read in the raw images from the Optical Devices, pass them through a filtering algorithm, and then determine a navigation decision based on what the filtering algorithm finds. This navigation decision is then sent to the SPU for further manipulation.

For constraints, the IPU needs to be able to multi-thread in order to complete the filtering of the images in a reasonable amount of time. It also needs to consume less than 50-Watts, be capable of running Linux, and be fairly lightweight (1-3lbs).

Alternative Design Process

Initially, the SPU was chosen to handle images as well as other sensor data. As the semester progressed, we realized that if we had the SPU perform filtering for every sensor, it would not be completed in a reasonable amount of time and our whole system would be too slow, so we made the choice to go ahead and have a separate processor for the images only. Considerations for the IPU include a Mini-Windows PC and possible a multi-core microcontroller and will be explored more in depth over Winter Break

Testing

No testing of the IPU has taken place yet, as we have not purchased it or made a final decision on it. Testing is expected to start in the Spring, with tests including speed, power consumption, and reliability testing.

Risk Mitigation

Possible hardware risks associated with the IPU include failure to boot, failure to receive or transmit data, or failure to meet processing speed requirements. These can be mitigated by extensive testing of the IPU and connecting systems before even submerging, and an error / boot LED attached to the IPU itself. If it is simply not fast enough, it will be replaced.

Master Control Unit

Objective and Constraints

The hardware objective of the Master Control Unit (MCU) is to be able to take processed data from the SPU and convert it into readable data for the motor controller. For this, the hardware just needs to be fast enough to convert this data, weigh less than 1-pound, consume a minimal amount of power, and have the correct I/O interfaces to receive data from the SPUs and output new data to the motor control unit.

Alternative Design Processes

Initially, the MCU was more in the hands of the propulsion/power sub-team, as they need it for more than the sensors sub-team does, as our SPU/IPU will handle all of our sensor data processing. They had discussed having an OS-capable mini-computer, a microcontroller, and even a Field Programmable Gate Array. As the semester progressed, the MCU was transferred to the hands of the sensors sub-team, and we are still unsure if we need the MCU to have OS-capabilities or not. We do know that it does not need to be as powerful as the SPU or IPU, as they are handling the raw data. Therefore, the only remaining constraints are that it has the necessary input ports for the SPU and motor controller output.

Testing

No hardware testing of the MCU has been done at this point. Testing of the actual MCU is not expected to be done until the Spring Semester, as each subsystem can be tested without the MCU. When these tests do begin, they are expected to include I/O, speed, and power consumption tests.

Risk Mitigation

Possible hardware risks associated with the MCU include failure to boot, failure to receive or output data, or failure to meet the speed required. To mitigate these risks, the MCU will be tested before going into the water to ensure booting and I/O functionality, and it will also be equipped with an LED for booting and I/O failure. If the MCU simply is not fast enough, it will be replaced

Software

Sensor Processing Unit

Objectives and Constraints

The software objective of the SPU is to be able to take in raw sensor data, perform certain operations on the data, such as filtering and positional transformation, and then convert this processed data into a navigation decision which will then be outputted to the MCU for further processing.

To accomplish this, the software needs to be able to quickly receive data, process it, and output a navigation decision, a matter of 300ms max for all data from the IPU, IMU, and pressure sensors.

Alternative Design Processes

Initially, software languages considered for this objective included C, C++, Java, and Python. Knowing that we had to make a decision quickly for testing purposes, the sensors sub-team voted on a consensus that Python would be used, as it is open source and is easy to learn.

Testing

Extensive software testing of the SPU has been done. Although not physically done on the SPU itself, actual test data has been retrieved from the IMU and run through Python code.

For the IMU, simulations have been done using Matlab to simulate Gaussian noise in our IMU. Our real position was compared to a simulated position based on our signal-to-noise ratio. Actual test data from our test IMU has been run through python code to attempt to map our current position compared to where the IMU was actually moved.

Risk Mitigation

Software risks associated with the SPU are numerous. These include: failure to retrieve filtered images, inertial data, or pressure data, failure to correctly filter pressure or inertial data, failure to correctly identify the pressure read from the Pressure Transducers, failure to complete the processing in enough time, and failure to initialize code. To mitigate these possible failures, the SPU will be equipped with an error and boot indicator LED, be extensively tested before being submerged, and send out test data while being submerged for tests to correct any errors found.

Image Processing Unit

Objectives and Constraints

The objective of the IPU software is to retrieve raw images from the camera, filter the images to find the position of the tape line at the bottom of the pool, and decide which way to move based upon the position of the line.

The constraints of the IPU software are that it needs to be fast and efficient in making a movement decision for the sub (300ms max per image) so that way we do not collide with obstacles.

Alternative Design Processes

Initially, as with the SPU, several programming languages were considered, including C, C++, Java, and Python. With the whole sensors sub-team consensus on Python, it was the language also chosen for the IPU as a means of easy readability by the sub-team. It has not been changed, and the only difference from the SPU software is that a plugin known as OpenCV is being used to aid in image processing.

Testing

Extensive software testing of the IPU has been completed on a desktop computer. Filtering algorithms have been run and tested to see how well the algorithms work and how quickly they work. These tests and the values of filters will need to be adjusted when the actual IPU is purchased. Below are the tests so far.

The raw images, which had an orange line drawn in them indicative of the line to be followed in the competition, were initially passed through a blurring filter, a threshold filter to remove smaller shapes, an edge filter to find contours, and finally a probabilistic line transform to draw a new line which would then be used for movement decisions. This was found to not work very well on curved lines, which would cause the vehicle to veer off course in an actual test environment.

Next, a “skeleton” method was tested, in which the original line was filtered to form a skeleton, and then the probabilistic line transform was performed on this skeleton. Again, this did not work very well on curved lines. A new and final approach was then tested. In this final approach, the original image was filtered in order to find the largest contour (the line which we want to follow) and a region-of-interest (ROI) was drawn around the line. Next, the ROI was masked to the original image in order to black out anything that was not within the ROI. Finally, the ROI-masked image was filtered so that only the orange of the tape would be seen as red, while everything else is converted to black.

The software has not yet been developed that will test the position of this line in the original image, as it will be needed to make navigation decisions. This is to be worked on and tested over Winter break.

Risk Mitigation

Possible software risks with the IPU are similar to the SPU. These include failure to load images, failure to correctly filter images, failure to complete filtering in a timely manner, failure to output filtered images, and failure to initialize code. TO mitigate these, the software will be extensively tested before being submerged, be equipped with a failure / boot LED, and have various checks throughout the code.

Master Control Unit

Objectives and Constraints

The objective of the MCU software is that it will take in processed sensor data and convert it to a usable format that the motor controller will use. The only constraint for this is that the software be fast enough to not cause a collision.

Alternative Design Processes

From the beginning, we had planned on the MCU not doing intensive processing, as this would be left to the SPU and IPU, and also that it would only convert navigation data to a format the motor controller can use. This idea has not changed, and the software is still as simple as converting data.

Testing

The software for the MCU has not yet been tested, as the SPU and motor controller software can be tested independently of the MCU. Tests on MCU software are expected to begin in the Spring Semester, when both the sensors and propulsion/power sub-teams have been able to develop software for the SPUs and motor controllers separately. These tests will include speed and reliability tests.

Risk Mitigation

Possible software risks include: failure to read-in navigation data from the SPUs, failure to handle navigation data in a timely manner, failure to output readable data for the motor controller, and failure to initialize code or boot.

To mitigate these possible risks, the MCU will be tested extensively before being submerged, be equipped with an error and boot LED, and will output data to a surface computer for testing while submerged.

Chapter 6 – Power and Propulsion Sub-team

Hardware

Motor Processing Unit

Objectives and Constraints

The purpose of the motor processing unit is to coordinate and control the motor drivers. There were no constraints on what kind of MPU could be used, so all of the following constraints were imposed by the sub team. The MPU has to have the ability to communicate, at least, via I^2C, CAN, and SPI so any master control unit chosen can receive a signal from the MPU. The MPU also needs a means of communicating result back to the user because that is the only way this device will be testable. On top of the communications requirement, the MPU must also have high resolution in order to have as many states as possible since just being on and off is not going to be efficient. The vehicle also needs to be able to slow itself which requires braking and the ability to reverse in the case that the vehicle overshoots an objective or runs into an obstacle.

Alternative Design Processes

The separation of the MPU and the MD for this iteration of the project is for rapid prototyping. The separation of these two devices is not actually necessary because the MPU has dedicated PWM channels. Depending on the design, the number of PWM channels needed is number of motors multiplied by three since there are going to be three phases per motor. The MPU can then handle all of the switching that the MD does, thus removing the necessity of the MD. This does however, require the use of off board IGBT's or Power FET's to handle the current and voltage.

Testing

The following are the tests that the MPU is going to be subject to: flash test, maximum power consumption, state, and mode. These tests are the core of what we need to know about the device from a system and component point of view. These tests satisfy the requirement of two-way communication, possible motor states, and whether or not the MPU can have a forward, braking, and reverse mode.

See Appendix H for more information. Also see Figure 4P and [14P] for reference.

Motors

Objectives and Constraints

The purpose of the motors is to translate electrical energy into a mechanical energy characterized by several electrical and mechanical constraints.

There are 6 degrees-of-freedom the vehicle is bound by: 3 kinematic linear axes and 3 kinematic rotations about each linear axis respectively. This means there must be at least 6 coordinated motors allowing for the dynamic positioning required by the mechanical team.

The weight of each motor cannot be significant due to the 125 lb. limitation of the competition rules: to keep a reasonable initial working basis, the propulsion team decided that motors, in total, should weigh no more than 6 lb. or roughly 1 lb. per motor.

Competition rules limit that maximum operating voltage to 48 VDC but the actual voltage for the motors (and thus battery system) are substantially reduced due to cost and commercial availability: 48 VDC systems are extremely expensive in both lithium battery technology and BLDC motors. Also, 48 VDC motors are built for larger loads and usually start around 25 lb. per motor. AC motors (AC in the driver sense) are not applicable due to large size and are generally far heavier than their DC counter parts. Lastly, 3-phase BLDC motors have become common place replacing the single and double pole brushed DC motors produced up till recently: 3-phase is cheaper and easier to find which allows the team to find motor replacements without major hardware/software rework years from now.

Torque is critical in moving the vehicle: with the vehicle slowing down (drag plus any dynamic braking), speeding up, and changing direction the motors must be able to respond to the varying load characteristics which are a function of the water viscosity, speed, and vehicle geometry. DC motors excel at torque intensive applications. Since torque is realized in amperage and given the 14.8 V limitation imposed by cost and weight, the power supply must be able to supply the motors with at least the maximum current draw plus some allowance for inrush.

Other constraints for motors come as a consequence of the utilization of naked motors for the prototype phase. Those constraints include waterproofing via either PVC or hard machinable wax, building of an in-house shroud of the motor propeller, integrated mounting system for the motor, and custom propeller design.

A LiPo based motor system weighing .6 lb. per motor running at 14.8 V (nominal) with a 30 A draw (burst) and quiescent current of 1 A satisfies the size, cost, and torque constraints and while providing a cheap "learning" platform for the prototype phase. If successful, additional batteries and motors will be implemented on the final vehicle.

Alternative Design Processes

At the beginning of the Fall 2016-2017 evolution of the RoboSub vehicle, it was presumed that off-the-shelf motors would be purchased from Blue Robotics and used with little regard other than they are *designed* for the RoboSub competition. It was discovered during the research phase that it may be possible to reduce costs by approaching the problem from a more “hands-on” manner, with the caveat that more time and testing would be required to realize the propulsion stage.

Testing

Essential tests for motors are: load characterization, no load characterization, waterproofing, and heat-up testing. These four essential test inform us as to whether the naked motors can be used for not only the physical responses (torque) but the working limits (environment and heat). It also anticipated that these tests for a baseline for future teams to plan and develop upon.

Additional testing will be performed as a coordination test. This test answers latency and response of commands sent to the motors from both the ESC and MPU. It allows for tweaking of software delays and values in accordance with the physical variances of the motor, ESC, BMS, and power source.

See Appendix H for a more detailed explanation of specific tests to be conducted. Also see Figure 1P in Appendix F as well as [6P] for reference.

Power Source

Objectives and Constraints

The purpose of the power source is to provide power at the appropriate input voltages and required amperages to all subsystems of the vehicle: motors, MPU, MCU, OP, SD, ESC, lighting, relays, and any other subsystems that may be added as a consequence of the prototype phase. Due to independence of the team and the variety of subsystems, voltages range from 3.3 V to 14.8 V and 1 mA to 30 A. In addition, the power system must not be mains powered (RoboSub rules constraint). This essentially means super capacitors or chemical batteries must be used.

The two largest and dictating design constraints come from motors and the competition rules. Competition rules force an upper limit constraint of 48 VDC while the team constraints further limit that to 14.8 V (nominal), which comes out of the overall fact that higher voltage motors are heavier and more expensive. The motors constrain total instantaneous deliverable amperage: each motor impulse of 30 A for 6 motors gives an upper bound of around 180 A. While this is not realistic for a 20 minute run time, it at least provides some of the most extreme behavior that is expected out of the vehicle during testing.

These two constraints narrow the choices we have at our disposal: NiMH and NiCd--while cheap--cannot supply the burst current; bench-top power supplies cannot be used to power the vehicle underwater at 20 feet deep due to voltage drop. Therefore, only lithium-based batteries can be used: only lithium batteries allow us to keep battery weight low without limiting current response.

Alternative Design Processes

The initial design process involved using of a cheap battery in the prototype phase and a benchtop power supply during benchtop testing.

NiCd and NiMH require a parallel capacitor bank to allow for the high amperage demand used during the impulse of motors from off to full-on. In addition, NiCd and NiMH have lower voltage levels. These two factors make a test battery composed of NiCd or NiMH just as costly as a mid-high range LiPo but almost 10 the weight: 6 NiCd/NiMH batteries would come in around 10 lb. which is almost 10 times the weight of the LiPo (1.2 lbs).

A benchtop power supply is extremely useful but finding of a higher amperage lower voltage benchtop power supply proved costly and could not allow modeling of system response (motor, controllers, etc.) under a falling voltage level. These two facts eliminate the usage for system characterizations. However, it is still maintained that given the monetary resources a benchtop power supply could prove useful for programming and endurance testing of the motors.

Testing

Testing of the power supply is one of the easier schemes: by applying a varying load, the current and voltage can be measured over time to give the characteristic curves of the battery. These curves can be used to assess the expected system response and account for those responses in software if necessary. It also allows to design to specific battery behavior: no two batteries are exactly the same and tweaking of the ESC or BMS values (voltage and current) will be necessary.

Any destructive testing of the battery is prohibited, mainly due to cost. It is assumed that the IP68 rating and durability of the battery is in accordance with the manufacturers specifications. Also, due to the destructive nature of running LiPo cells under a 3.0 V level, the BMS must be used at all time with the LiPo cells to prevent permanent damage to the cells.

See Appendix H for a more detailed explanation of specific tests to be conducted. Also see Figure 2P in Appendix F and [21P] for reference.

Battery Management System

Objectives and Constraints

The purpose of the battery management system is to monitor the behavior of the cells in the battery. The only constraint from the competition was that every vehicle has to be powered by batteries. Any lithium based battery requires the use of a BMS, due to the thermal properties of lithium as an element. Lithium cells are more unstable and tend to get into runaway states so by virtue of our choice of battery, a BMS becomes a requirement. The BMS needs to perform the following functions: cell balancing, cell monitoring, overvoltage protection, and enforce low voltage drop-out.

The BMS is not only for the health of the batteries, but also for the safety of the team. Since lithium based batteries do have the potential to enter a runaway state, which can result in the battery catching fire or even exploding, the BMS is a method for preventing potential hazards to the team.

Alternative Design Processes

The choice of power supply dictates the necessity of having a battery management system. Non-lithium based power supplies such as NiMH and NiCd, do not require the use of a battery management system.

Testing

The following is the test that the BMS is going to be subject to: communications test. The BMS needs to disconnect the power supply in the case there is a fault condition detected in the power supply, as wells as disconnect the power supply when a fault condition is detected in one of the other subsystems. Thus, the communication test verifies that the BMS can send and receive a signal.

See Appendix H for a more detailed explanation of specific tests to be conducted.

Motor Driver

Objectives and Constraints

The motor drive translates PWM signals from the MPU via some type insulated gate driver stage which drives an inverter stage of power semiconductors in either a half-bridge or full-bridge configuration on a DC bus provided by the power source.

In order to produce a prototype faster and prevent getting in the quagmire of complex system design, the propulsion team has elected to use an ESC in replacement of a custom MD. What makes the prototype phase faster the software: software is usually the most complex part of the MD along with the feedback hardware. Phase synchronization is now handled by the feedback and microcontroller hardware/software on the ESC. This eliminates the need for the team to figure out phase synchronization before any testing of the motor occurs. It also allows the team to reduce cost: ESCs are cheap and easily replaceable while custom MD are much more expensive due to lack of production quantity effects.

To match the motor characteristics, the ESC must be able to handle up to 30 A per phase (3 phases on the BLDC) at 14.8 V nominal. Apart from this, the ESC must be handle the Blue Robotics open-software which splits the incoming PWM into a lower and upper band. This allows us to run the motors in forward, reverse, and stop.

Alternative Design Processes

The original intent of the propulsion team was to purchase a highly capable MD from a reputable vendor. However, it became evident very quick that the cost of handling 180 A at 14.8 V (nominal) was a very difficult task: most drivers designed as embedded systems (MPU+MD) didn't meet the current requirements and those that did were not designed with usage of 3 phase BLDC motors in mind. This quickly lead us to consider splitting a unified MD into several

MD. This in turn raised the complexity of building an MD: we realized the development of a custom MD at this stage was too complex to be accomplished in the timetable developed.

Testing

There are several simple low-level tests that must be done first thing with the ESC: the MPU must be hooked up and configured to see if the ESC can be communicated with and that the ESC is receiving the proper PWM signals to translate into a motor actuation.

The ESC must be reprogrammed or "re-flashed" with the Blue Robotics software in order to capitalize on the split-band forward/reverse functionality that Blue has programmed for.

In order to keep the mechanical engineers cooling of the electrical housing effective, the amount of heat produced by the inverter stage under varying power loads must be measured.

Lastly, coordination testing must be done from the MPU to at least two ESCs. This will inform the prototype phase about how multiple motors can be coordinated from the MPU and what hardware, if any, may be necessary.

See Appendix H for a more detailed explanation of specific tests to be conducted. Also see Figure 3P in Appendix F and [11P] for reference.

Software

Motor Processing Unit

Objectives and Constraints

The objective of the software for the MPU is to allow us to quickly accommodate for different types of motors as well as tune the response of the motor control. The software on the MCU must have a simplified HMI as well since this project is on a short time table. Although we are not going to be utilizing the FOC ability of the MPU for this iteration of the project, it makes integrating the MPU and MD stages of the project together much easier for future teams.

Alternative Design Processes

The only alternative to using some pre-built software would be going in and writing it all yourself. As we are on a very restricted timetable, this approach was not adopted for this iteration of the project.

Testing

The most important functions that the software of the MPU are that it boots and that it can be written to.

See Appendix H for a more detailed explanation of tests to be performed.

Battery Management System

Objectives and Constraints

The objective of the software for the BMS is to allow us to quickly accommodate for different types of batteries and number of cells. The software on the BMS must have a simplified HMI because the BMS has to be rapidly implementable in order for the testing to proceed for the vehicle. This feature also ensures that the team is as safe as possible while testing the battery.

Alternative Design Processes

Very similar to the MPU, the only alternative to using a prebuilt software package is to write your own software.

Testing

The tests that will inform us of our requirements are: boot test and flash test. The boot test will tell us that the device is functional and the flash test will tell us that the BMS is programmable.

See Appendix H for a more detailed explanation of tests to be performed.

Chapter 7 – Future Work

Due to setbacks in funding and agreement among the team regarding personal spending, the entire team has experience a delay in the prototype testing and manufacture time scope. However, the team estimated such setbacks as this and accounted for a 3 month run-over time. This simply means: the entire team experiences a shift of the prototype testing and manufacture by one month; to be completed by February 1st rather than January 1st.

Mechanical

The mechanical sub-team plans to begin purchasing, manufacturing, testing, and redesigning accordingly. Using the team's industry resources, the mechanical team plans on using the advice from engineers in the field during the second semester. Using local and online vendors, materials will be purchased for all components needed. Using these components, the mechanical team will be manufacturing and modifying the materials. The manufacturing process will be done using tooling from the school and team mentors. The mechanical team will be conducting the tests listed in the DTVC (Appendix H). From the results of these tests, necessary redesigns will be made.

Sensors

For the future work of the sensors sub-team, we plan on purchasing our actual sensors, SPU, and IPU, and once we have them we will begin real-world testing. This will mean mounting our sensors in a test rig to collect data, analyzing that data, and adjusting our programs accordingly. Our camera will collect actual images of tape at the bottom of a pool, our IMU will get actual water movement data, and our pressure sensors will be tested for the first time. This data will then be tested against our programs that we have already made to see how far off our simulations are from the real world. Then, hopefully, only values of our programs will need to be changed, not the entire structure of the programs. Once our test rig data is accounted for, we hope that only slight adjustments will need to be made when the final rig is built.

We also plan on re-organizing all of our Python directories in a standard, modular format so that in case we switch any part of our system out, it will just require us to change one section of code, not the entire program. Finally, we'll want to begin writing code for the MCU to make movement decisions.

Propulsion and Power

From the standpoint of the power and propulsion sub-team, this delay has not been a waste: it has afforded the team to verify their calculations which has caught two errors in ordering so far.

The Spring 2017 future work commencing December 2016 until February 1st 2017 includes:

- Motor load testing
- Current, Voltage, Power under various "modes" of entire system
- Design/Testing of a variety of propellers and shrouds
- Thermodynamic Data Collection from subsystems
- Vetting of BMS

From February 1st 2017 until April 1st 2017:

- PCB for BMS
- PCB for IMU
- PCB for Systems Integration
- Additional motors and PID control development

From April 1st 2017 until May/June 2017, it is intended to finalize whatever work is left in progress and prepare the vehicle for E-days.

For a full description of the Power and Propulsion sub-team timeline, please see Appendix C.

References

[1M] "Parker O-Ring Handbook," in parker.com/orings, 2007. [Online]. Available: https://www.parker.com/literature/ORD%205700%20Parker_O-Ring_Handbook.pdf. Accessed: Dec. 6, 2016

[2M] J. Heiszwolf, "Submarine technology," 1999. [Online]. Available: http://www.heiszwolf.com/subs/tech/tech01.html. Accessed: Dec. 7, 2016.

[1S] A. Rosebrock, "Be awesome at learning OpenCV, python, and computer vision," PyImageSearch, 2016. [Online]. Available: http://www.pyimagesearch.com/. Accessed: Dec. 7, 2016.

[2S] "OpenCV documentation index,". [Online]. Available: http://docs.opencv.org/. Accessed: Dec. 7, 2016.

[3S] "Stack overflow," 2016. [Online]. Available: http://stackoverflow.com/. Accessed: Dec. 7, 2016.

[4S] A. V. T. GmbHImprint and Legal, "Digital industrial camera solutions," 2016. [Online]. Available: https://www.alliedvision.com/en/digital-industrial-camera-solutions.html. Accessed: Dec. 7, 2016.

[1P] AUVSIFoundation.org. 2016, 2, 12. *RoboSub Competition Official Rules and Mission* (2015). Available: http://higherlogicdownload.s3.amazonaws.com/AUVSI/fb9a8da0-2ac8-42d1a11ed58c1e158347/UploadedFiles/RoboSub%20Competition%20Official%20Rules%20and%20Missi on%20-%202015.pdf

[2P] Jared Carter (EE), Sam Johnson (EE), Will Nordahl (EE), Will Winward (EE), Arrol Bryant (ME), Austin Root (ME), Jocelyn Thompson (ME), Mathias Fochs (MET), Jacob Jenks (CS), Nathan Robertus (CS). *Montana State University Autonomous Underwater Vehicle: Development and Testing of the AUV "Blue November"*. Available: http://higherlogicdownload.s3.amazonaws.com/AUVSI/fb9a8da0-2ac8-42d1-a11ed58c1e158347/UploadedImages/2015%20RoboSub%20/Journal%20Papers/MontanaState_Journ al_RS2015.pdf

[3P] AUVSIFoundation.org. 2016, 2, 12. *18th Annual International RoboSub Competition* (2015). Available: http://www.auvsifoundation.org/competitions/competition-central/robosub/pastrobosub-competitions/2015-robosub

[4P] Justin Koch, Kushal Agarwal, Solomon Chang, Erin Evans, David Flicker, Edward Fouad, Jake Larson, Torkom Pailevanian, Sarah Asano, Brian He, Juliana Kew, Monica Li, Tristan Murphy, Tyler Okamoto, Jeffrey Orenstein, Frank Zhou, Roman Zograbian. 2015, 6, 19. *Design and Implementation of an Integrated, Performant Autonomous Underwater Vehicle*. Available: http://higherlogicdownload.s3.amazonaws.com/AUVSI/fb9a8da0-2ac8-42d1-a11ed58c1e158347/UploadedImages/2015%20RoboSub%20/Journal%20Papers/Caltech_Journal_Pap er_RS2015.pdf

[5P] Pierson Connors, Kyle Harlow, Sean Harrison, Kimi Bourland, Andrew Wydle, Josh Bowen, Kassi Butler, Rod Jafari, Alexander Silverman, Michelle Athay, Daaym Sial, Sam Forgy, Neal Kornreich, Ryan Niedzinski, Matt Salzer, Camella Nasr, Dylan Bossie. *University of Colorado Boulder RoboSub Team: WaterBuffalo II*. Available: http://higherlogicdownload.s3.amazonaws.com/AUVSI/fb9a8da0-2ac8-42d1-a11ed58c1e158347/UploadedImages/2015%20RoboSub%20/Journal%20Papers/Caltech_Journal_Pap er_RS2015.pdf

[6P] Robot Shop. (2016, December 6). *TMotor UAV Brushless Motor MS2814 770Kv* [Online]. Available: http://www.robotshop.com/en/tmotor-uav-brushless-motor-ms2814-770kv.html#Specifications

[7P] Blue Robotics. (2016, December 6). *T200 Thruster* [Online]. Available: https://www.bluerobotics.com/store/thrusters/t200-thruster/

[8P] Blue Robotics. (2016, December 6). *T200 Thruster Specifications* [Online]. Available: http://docs.bluerobotics.com/thrusters/t200/#t100-thruster-specifications

[9P] Blue Robotics. (2016, December 6). *30 A ESC w/ Forward & Reverse* [Online]. Available: https://www.bluerobotics.com/store/thrusters/besc-30-r1/

[10P] Git Hub. (2016, December 6). *blue robotics\tgy* [Online]. Available: https://github.com/bluerobotics/tgy/

[11P] HobbyKing. (2016, December 6). *HobbyKing 40A BlueSeries Brushless Speed Controller* [Online]. Available: https://www.hobbyking.com/en_us/hobbyking-40a-blueseries-brushless-speed-controller.html

[12P] Texas Instruments. (2016, December 6). *The TMS320F2837xD Architecture: Achieving a New Level of High Performance* [Online]. Available: http://www.ti.com/lit/pdf/sprt720

[13P] Texas Instruments. (2016, December 6). *TMS320F2837xS Delfino Microcontrollers Technical Reference Manual (Rev. C)*. [Online]. Available: http://www.ti.com/lit/pdf/spruhx5

[14P] Texas Instruments. (2016, December 6). *LAUNCHXL-F28377S Overview User's Guide (Rev. A)*. [Online]. Available: http://www.ti.com/lit/pdf/sprui25

[15P] Texas Instruments. (2016, December 6). *TMS320F28377S LaunchPad Quick Start Guide* . [Online]. Available: http://www.ti.com/lit/pdf/sprui26

[16P] Texas Instruments. (2016, December 6). *3 to 5-Series Cell Li-Ion and Li-Phosphate Battery Monitor (bq76940 Family)*. [Online]. Available: http://www.ti.com/product/BQ76920

[17P] Texas Instruments. (2016, December 6). bq769x0 3-Series to 15-Series Cell Battery Monitor Family for Li-Ion and Phosphate Applications (Rev. G). [Online]. Available: http://www.ti.com/lit/gpn/bq76920

[18P] Beaver Lake Boaters. (2016, December 6*). Do Your Props Have the Right Cup, Rake, Slip, Pitch and Hub?* [Online]. Available: http://www.beaverlakeboaters.net/boating/doyourpropshavetherightcuprakeslippitchandhub/

[19P] Allen Bradley. (2016, December 6*). AC Drives Using PWM Techniques.* [Online]. Available: https://www.ab.com/support/abdrives/documentation/techpapers/PWMDrives01.pdf

[20P] MPS. (2016, December 6*). Brushless DC Motor Fundamentals Application Note*. [Online]. Available: https://www.monolithicpower.com/Portals/0/Documents/Products/Documents/appnotes/Brushless%20DC%20Motor%20Fundamentals.pdf

[21P] MaxxAmps. (2016, December 6). *LiPo 8000 4S 14.8v Dual Core Battery Pack*. [Online]. Available: https://www.maxamps.com/lipo-8000-4s-14-8v-dual-core-battery-pack

[22P] "Johnson Matthey battery systems-battery management system," in *Johnson Matthey Battery Systems*, 2014. (2016, December 6). [Online]. Available: http://www.jmbatterysystems.com/technology/battery-management-systems-(bms)

Appendix A – Abbreviations

A

ABS	Acrylonitrile Butadiene Styrene
AUV	Autonomous Underwater Vehicle

B

BMS	Battery Management System
BLDC	Brushless Direct Current Motor

C

CAD	Computer Aided Drafting
CAN	Controller Area Network bus
CE	Computer Engineer
CFD	Computational Fluid Dynamics
CO2	Carbon Dioxide

D

DS	Delta-Sigma modulation
DOF	Degrees of Freedom
DTVC	Device Test Validation Characterization

E

EE	Electrical Engineer
EFD	Electronic Failure Device
ESC	Electronic Speed Control

F

FET	Field-Effect Transistor
FMEA	Failure Mode Effect Analysis

G

GPIO	General-Purpose Input/Output

H

HFD	Human Failure Device
HMI	Human Machine Interface

I

I^2C	Inter-integrated Circuit bus
IGBT	Insulated-Gate Bipolar Transistor
IMU	Inertial Measurement Unit

L

lb-f	Pound-Force
LED	Light Emitting Diode
LiPO	Lithium Polymer or Lithium Ion battery

M

MCU	Master Control Unit
MD	Motor Driver
ME	Mechanical Engineer
MPU	Motor Processing Unit
m/s	Meters per Second

N

NiMH	Nickel Metal Hydride
NiCd	Nickel-Cadmium

O

OS	Operating System

P

PI	Performance Index
PLA	Polylactic Acid
PVC	Polyvinyl Chloride
PWM	Pulse Width Modulation

S

SD	Sensor Devices
sec	Seconds
SPI	Serial peripheral interface bus
SPU	Sensor Processing Unit

U

UART	Universal Asynchronous Receive/Transmit bus

R

ROI	Region of Interest

W

W	Watts

Appendix B – Budget

Estimated Budget At-A-Glance:

Item	*Cost*
Motors	$1800
Motor Control / MicroControl	$1000
Power Supply	$800
Sensors	$2500
MISC	$1000
Final Vehicle Chassis	$1500
Prototype Vehicle Chassis	$800
Mechanical Blunders	$1000
Electrical Blunders	$1300
Total	$11,700

Figure 8 – Budget

Budget Breakdown:

-Motors

The dollar allotment for the motors will be utilized in the purchase of 6 Brushless DC motors.

Motors	$ 1800

-Motor Control

Two motor controllers with 2-3 channels per controller coordinated by one Master RMCU.

Primary RMCU	$ 400
Motor Microcontrollers	$ 600

-Power Supply

Power supply consists of two batteries: one battery powering controls and the second powering motors.

Battery Power Supply	$ 700
Controller Power Supply	$ 100

-Sensors/Optics

The IMU is used for navigation in conjunction with cameras. The HS is used for beacon location, and possible navigation.

Inertial Measurement Unit	$ 1200
Hydrophone System (HS)	$ 800
Signal Amplifiers	$ 100
Underwater Cameras	$ 400

-Miscellaneous

All of the connectors will be insulated and water tight.

Connectors	$ 500
Gaskets	$ 70
Wires	$ 200
Mechanical Tether	$ 30
Electrical Tether	$ 200

-Prototype Test Vehicle

These are the materials for a preliminary test vehicle.

Clear Acrylic Body	$ 600
Sealants	$ 50
Hardware	$ 150
Battery	$ 250
Motors	$ 1200
Inertial Measurement Unit	$ 1200
Underwater Cameras	$ 400
Primary RMCU	$ 400
Motor Microcontrollers	$ 300
Connectors	$ 500
Gaskets	$ 70
Wires	$ 200
Mechanical Tether	$ 30
Electrical Tether	$ 200
Total	$ 5550

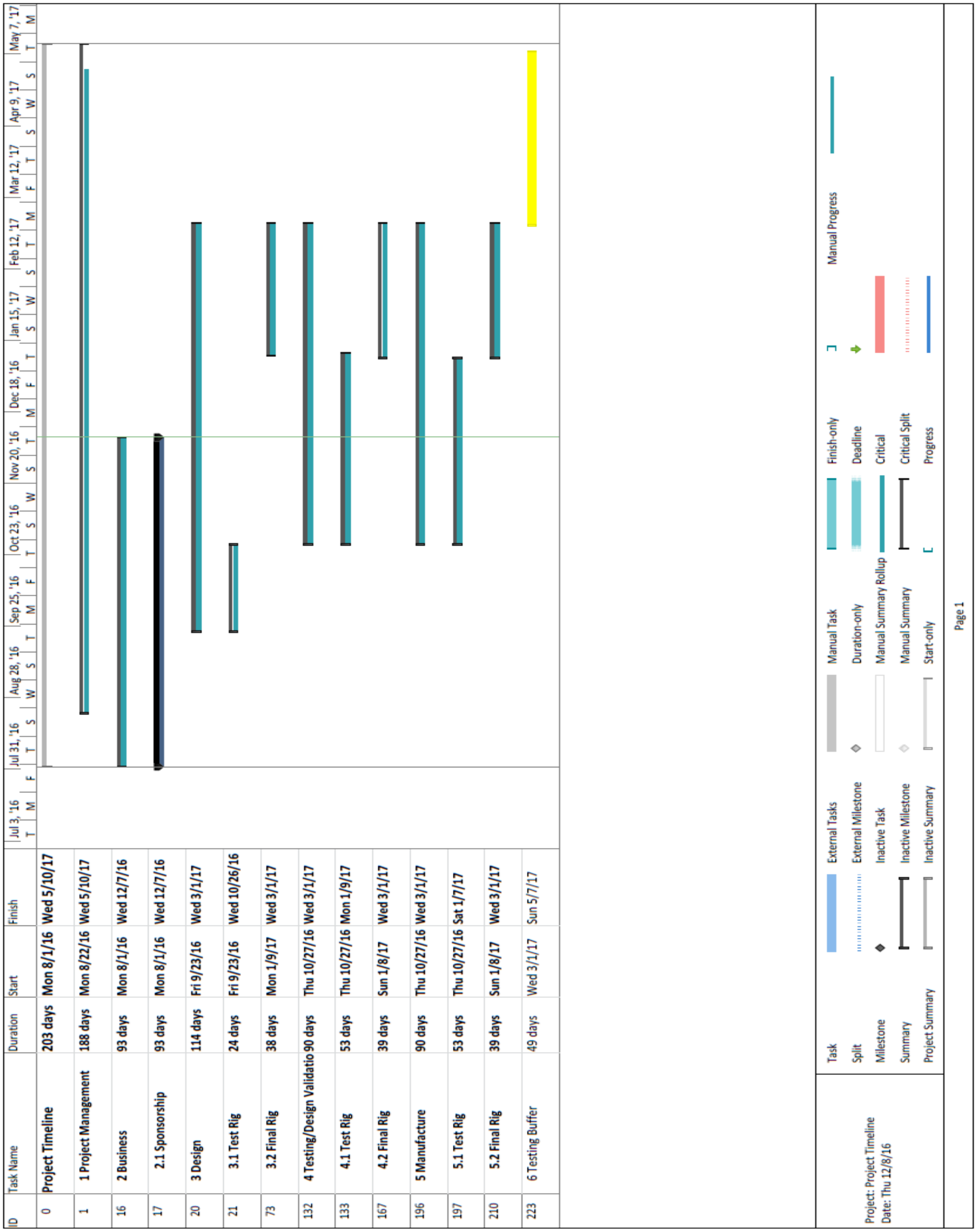
-Mechanical Reserve

Loss in Materials	
Mechanical Mismatch	$ 100
Poor Manufacturing	$ 700
Leaks (Outer Hull)	
Replace seals	$ 200

-Electrical Reserve

Motor burn out	$ 600
Battery Damage/Failure	$ 700

Appendix C – Project Plan Evolution



ID	Task Name	Duration	Start	Finish
0	**Project Timeline**	**203 days**	**Mon 8/1/16**	**Wed 5/10/17**
1	**1 Project Management**	**188 days**	**Mon 8/22/16**	**Wed 5/10/17**
16	**2 Business**	**93 days**	**Mon 8/1/16**	**Wed 12/7/16**
17	**2.1 Sponsorship**	**93 days**	**Mon 8/1/16**	**Wed 12/7/16**
20	**3 Design**	**114 days**	**Fri 9/23/16**	**Wed 3/1/17**
21	**3.1 Test Rig**	**24 days**	**Fri 9/23/16**	**Wed 10/26/16**
73	**3.2 Final Rig**	**38 days**	**Mon 1/9/17**	**Wed 3/1/17**
132	**4 Testing/Design Validatio**	**90 days**	**Thu 10/27/16**	**Wed 3/1/17**
133	**4.1 Test Rig**	**53 days**	**Thu 10/27/16**	**Mon 1/9/17**
167	**4.2 Final Rig**	**39 days**	**Sun 1/8/17**	**Wed 3/1/17**
196	**5 Manufacture**	**90 days**	**Thu 10/27/16**	**Wed 3/1/17**
197	**5.1 Test Rig**	**53 days**	**Thu 10/27/16**	**Sat 1/7/17**
210	**5.2 Final Rig**	**39 days**	**Sun 1/8/17**	**Wed 3/1/17**
223	6 Testing Buffer	49 days	Wed 3/1/17	Sun 5/7/17

Appendix D – Failure Mode and Effects Analysis

Electrical Housing									Formula = (Rank/40)*R.O.O.*D		
Function	Performance Standards	Functional Failures	Failure Modes	Failure Effects	Consequence Category	Rank (Total out of 40)	Rate of Occurrence	Detectibility	Risk Ranking(0.1 = Lowest; 100 = Highest)	Normalized Rank (1= high, 0 = low)	Mitigation
Protection to electrical components	Dry environment	Water inside housing	Seal leaks	Electronics Damaged	Non functional Vehicle, electrical components unusable, seals	1 (E), 1(S), 9(O), 8(NO)	1	1	0.475	0.18627451	Design with multiple seals , water sensor initializes to cut power
			Housing fractures	Electronics Damaged	Non functional Vehicle, electrical components unusable, housing unusable	1(E), 1(S), 9(O), 8(NO)	1	1	0.475	0.18627451	Place moisture absorbant material inside, water sensor initializes to cut power
			Condensation	Electronics Damaged	Non functional Vehicle, electrical components unusable	1 (E), 1(S), 8(O), 7(NO)	3	2	2.55	1	Design housing to withstand 2X safety factor of max stress / Upon failure, humidity sensor initializes to cut power
	Heat dispation	Excess temperature	Electrical components fail	Vehicle does not function	Non functional Vehicle, electrical components unusable	1 (E), 1(S), 6(O), 5(NO)	3	2	1.95	0.764705882	Use proper heat dissipation with heat syncs and convection / Upon reaching elevated temperatures, heat sensor cuts power.
			Seals Melt	Shorts electronics	Non functional Vehicle, electrical components unusable, seals unusable	1 (E), 1(S), 9(O), 8(NO)	1	1	0.475	0.18627451	Use materials that exceed 2X safety temperature operation / Upon reaching elevated temperatures, heat sensor cuts power.
			Housing Fractures	Vehicle does not function	Non functional Vehicle, electrical components unusable, housing unusable	1(E), 1(S), 9(O), 8(NO)	1	1	0.475	0.18627451	Use materials that exceed 2X safety temperature operation / Upon reaching elevated temperatures, heat sensor cuts power.
	Isolation	Temperature threshold exceeded	Fire within vessel	Vehicle does not function	Non functional Vehicle, vessel unusable	5(E), 3(S), 9(O), 8(NO)	1	1	0.625	0.245098039	Design thermally isolated compartments / Upon reaching elevated temperatures, heat sensor cuts power.
		Damage to Components	Electrical components fail	Shorts electronics	Non functional Vehicle, electrical components unusable	1(E), 1(S), 7(O), 6(NO)	2	2	1.5	0.588235294	Design insulated compartments / Constant checks of electrical systems, any failure cut power

Ballast									Formula = (Rank/40)*R.O.O.* D		
Function	Performance Standards	Functional Failures	Failure Modes	Failure Effects	Consequence Category	Rank (Total out of 40)	Rate of Occurrence	Detectibility	Risk Ranking(0.1 = Lowest; 100 = Highest)	Normalized Rank (1= high, 0 = low)	Mitigation
Safely bring vessel to surface upon failure	Positive buoyancy upon electrical failure	Bag Does Not Inflate	Bag Tears	Sub does not surface	Bag unusable, water enters housing, electrical components damaged	1(E), 1(S), 10(O), 7(NO)	1	1	0.475	0.18627451	Choose bag material that withstand full CO2 ejection
			Bag Seal Breaks	Sub does not surface	Seal unusable, water enters housing, electrical components damaged	1(E), 1(S), 10(O), 7(NO)	1	1	0.475	0.18627451	Seals must withstant max pressure
			Obstuction of bag	Sub does not surface	Adjustment of bag needed	1(E), 1(S), 5(O), 1(NO)	3	2	1.2	0.470588235	Design must not have objects near bag
		C02 does not Eject	C02 Leaked	Sub does not surface	Co2 Cartridge unusable	1(E), 1(S), 7(O), 1(NO)	1	1	0.25	0.098039216	CO2 connector must withstand CO2 pressure
			Valve does not actuate	Sub does not surface	Valve unusable	1(E), 1(S), 10(O), 2(NO)	1	1	0.35	0.137254902	Choose reliable valve

Chassis									Formula = (Rank/40)*R.O.O.*D		
Function	**Performance Standards**	**Functional Failures**	**Failure Modes**	**Failure Effects**	**Consequence Category**	**Rank (Total out of 40)**	**Rate of Occurrence**	**Detectibility**	**Risk Ranking(0.1 = Lowest; 100 = Highest)**	**Normalized Rank (1= high, 0 = low)**	**Mitigation**
Protection to Components	Barier between components and harmful objects	Frame does not hold shape	Frame fractures	Components break	Components unusable, non functioning sub	1(E), 1(S), 9(O), 9(NO)	1	1	0.5	0.196078431	Choose strong material with at least 2X safety factor to max applied
				Components damaged	Components need repair, poor performance or nonfunctioning	1(E), 1(S), 7(O), 7(NO)	1	1	0.4	0.156862745	Choose strong material with at least 2X safety factor to max applied stress.
			Frame bends	Components break	Components unusable, non functioning sub	1(E), 1(S), 6(O), 6(NO)	2	1	0.7	0.274509804	Choose strong material with at least 2X safety factor to max applied
				Components damaged	Components need repair, poor performance or nonfunctioning	1(E), 1(S), 5(O), 5(NO)	2	1	0.6	0.235294118	Choose strong material with at least 2X safety factor to max applied stress.
		Joints become loose	Joints disconnect	Components break	Components unusable, non functioning sub	1(E), 1(S), 6(O), 6(NO)	1	1	0.35	0.137254902	Design joints to withstand 2X safety factor of max applied
				Components damaged	Components need repair, poor performance or nonfunctioning	1(E), 1(S), 5(O), 5(NO)	1	1	0.3	0.117647059	Design joints to withstand 2X safety factor of max applied stress
			Joints are unstable	Components break	Components unusable, non functioning sub	1(E), 1(S), 5(O), 4(NO)	2	1	0.55	0.215686275	Design joints to withstand 2X safety factor of max applied
				Components damaged	Components need repair, poor performance or nonfunctioning	1(E), 1(S), 5(O), 5(NO)	2	2	1.2	0.470588235	Design joints to withstand 2X safety factor of max applied stress
Holds Components in Place	Holds components rigidly	Frame is unstable	Components fall off	Components damaged	Components need repair, poor performance or nonfunctioning	1(E), 1(S), 6(O), 6(NO)	2	1	0.7	0.274509804	Design component connections to be able to withstand 2X safety factor of max stress
			Components shifted	poor performance	Components need adjustment	1(E), 1(S), 5(O), 1(NO)	4	2	1.6	0.62745098	Design component connections to be able to withstand 2X safety factor of max stress
				Components damaged	Components need repair, poor performance or nonfunctioning	1(E), 1(S), 5(O), 5(NO)	2	1	0.6	0.235294118	Design component connections to be able to withstand 2X safety factor of max stress

Appendix E – Mechanical Figures

Chassis		Designs					
Consideration	Importance	Box	Sled	Ram	UFO	X-wing	Classic
Cost	4	2.66	3.66	1.33	2.33	3.66	2
Adaptability	5	4.66	3.33	2	2.33	3.33	4
Part Aquisition	4	3.66	4	1.33	2.66	3.66	2
Weight	5	2	4.66	1.66	3.66	3.33	2.5
Size	5	2.33	4	2.66	3.66	3.33	2
Ease of Build	4	4	3.33	1	2.66	4	1.5
Durability	3	5	3.33	3.66	2.66	4	4
Strength	3	5	3	3	2.66	4	4
Ease of Repair	3	4.33	4.33	1.33	3	4.33	2
Time to Build	3	3.33	4	1.33	2.66	3.66	2.5
Protection	3	5	3	3.66	3	4	5
Portability	2	4.33	4.33	2.66	2.66	3.33	3
	Total:	162.87	165.55	90.5	126.11	161.86	123
	1	2	3				
Top 3:	Sled	Box	X-wing				

Figure 1M- Chassis Decision Matrix

		Designs				
Consideration	Importance	Half-Capsule	Half-Cylinder	Semi-Sphere	Box	Full-Cylinder
Cost	3	2.66	3.33	2	5	3.33
Strength	5	3.66	3	4	2.33	3.33
Water-Seal	5	4.66	3.66	3.66	2	3.66
Weight	4	3	3	3	3	3
Durable	5	3.66	3	3.33	2.66	3.33
Ease of Repair	4	2	2	1.66	4	3.33
Ease of Build	4	4	2.66	3.33	2.66	3
Part Acquisition	3	2.66	3.33	2.66	4.66	3.33
Time	3	4	3	3.66	3.33	3.33
Safety	3	4	3.66	3.66	3.33	3.66
	Total:	135.86	118.9	122.85	122.55	129.87
		1	2	3		
	Top 3:	Half-Capsule	Full-Cylinder	Semi-Sphere		

Figure 2M- Electrical Housing Decision Matrix

	Electrical Housing				Chassis				
	Dia (in)	Length (in)	Vol (Gal)	Buoyant Force EH (lb	Total 80-20 length (in	Weight of 80-20 (lb)	volume of 80-20 (ft^3)	Buoyancy force of 80-20 (lb)	Total buoyancy (lb)
	10	24	8.15997	67.97257308	372.48	16.38912	0.096805198	6.217797859	74.19037094
	10	25	8.49997	70.80476362	376.48	16.56512	0.097844773	6.284569744	77.08933337
	10	26	8.83997	73.63695417	380.48	16.74112	0.098884347	6.351341628	79.9882958
	10	27	9.17997	76.46914471	384.48	16.91712	0.099923922	6.418113512	82.88725822
	10	28	9.51997	79.30133526	388.48	17.09312	0.100963497	6.484885396	85.78622065
	10	29	9.85997	82.1335258	392.48	17.26912	0.102003071	6.551657281	88.68518308
	10	30	10.2	84.96571635	396.48	17.44512	0.103042646	6.618429165	91.58414551
Final Design	10	31	10.54	87.79790689	400.48	17.62112	0.104082221	6.685201049	94.48310794
	10	32	10.88	90.63009744	404.48	17.79712	0.105121796	6.751972933	97.38207037
	10	33	11.22	93.46228798	408.48	17.97312	0.10616137	6.818744817	100.2810328
	10	34	11.56	96.29447853	412.48	18.14912	0.107200945	6.885516702	103.1799952
	10	35	11.9	99.12666907	416.48	18.32512	0.10824052	6.952288586	106.0789577
	10	36	12.24	101.9588596	420.48	18.50112	0.109280095	7.01906047	108.9779201
	10	37	12.58	104.7910502	424.48	18.67712	0.110319669	7.085832354	111.8768825
	10	38	12.92	107.6232407	428.48	18.85312	0.111359244	7.152604239	114.7758449
	10	39	13.26	110.4554313	432.48	19.02912	0.112398819	7.219376123	117.6748074
	10	40	13.6	113.2876218	436.48	19.20512	0.113438393	7.286148007	120.5737698
Max	10	41	13.94	116.1198123	440.48	19.38112	0.114477968	7.352919891	123.4727322
	12	17	8.32317	69.33202454	363.76	16.00544	0.094538925	6.072235152	75.40425969
	12	18	8.81277	73.41037892	367.76	16.18144	0.0955785	6.139007036	79.54938596
	12	19	9.30237	77.48873331	371.76	16.35744	0.096618074	6.20577892	83.69451223
	12	20	9.79197	81.56708769	375.76	16.53344	0.097657649	6.272550804	87.8396385
	12	21	10.2816	85.64544208	379.76	16.70944	0.098697224	6.339322689	91.98476477
	12	22	10.7712	89.72379646	383.76	16.88544	0.099736799	6.406094573	96.12989104
	12	23	11.2608	93.80215085	387.76	17.06144	0.100776373	6.472866457	100.2750173
	12	24	11.7504	97.88050523	391.76	17.23744	0.101815948	6.539638341	104.4201436
	12	25	12.24	101.9588596	395.76	17.41344	0.102855523	6.606410226	108.5652698
	12	26	12.7296	106.037214	399.76	17.58944	0.103895097	6.67318211	112.7103961
	12	27	13.2192	110.1155684	403.76	17.76544	0.104934672	6.739953994	116.8555224
Max	12	28	13.7088	114.1939228	407.76	17.94144	0.105974247	6.806725878	121.0006486

Figure 3M- Housing Dimensions and Buoyancy

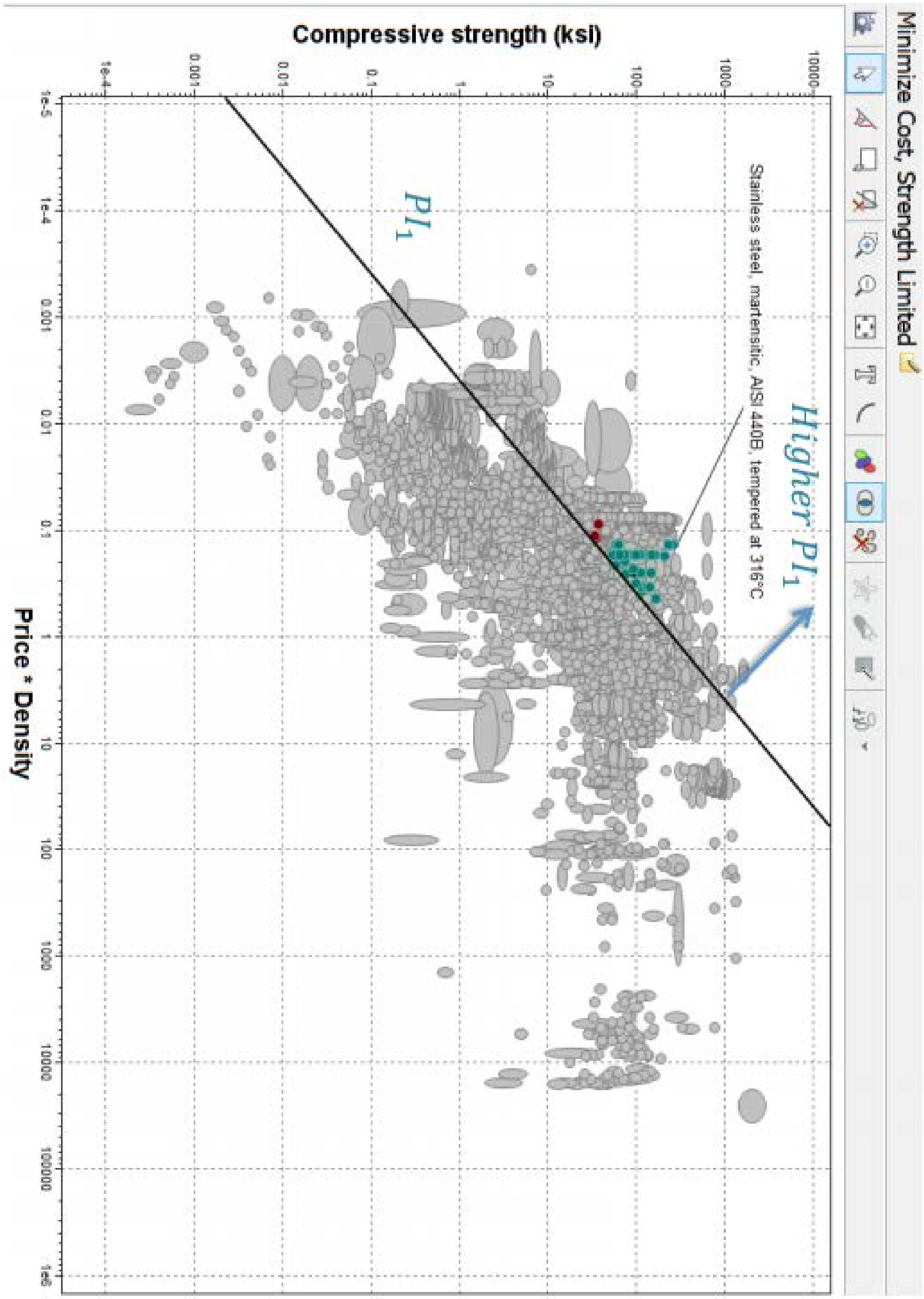


Figure 4M- Minimize Cost CES Graph

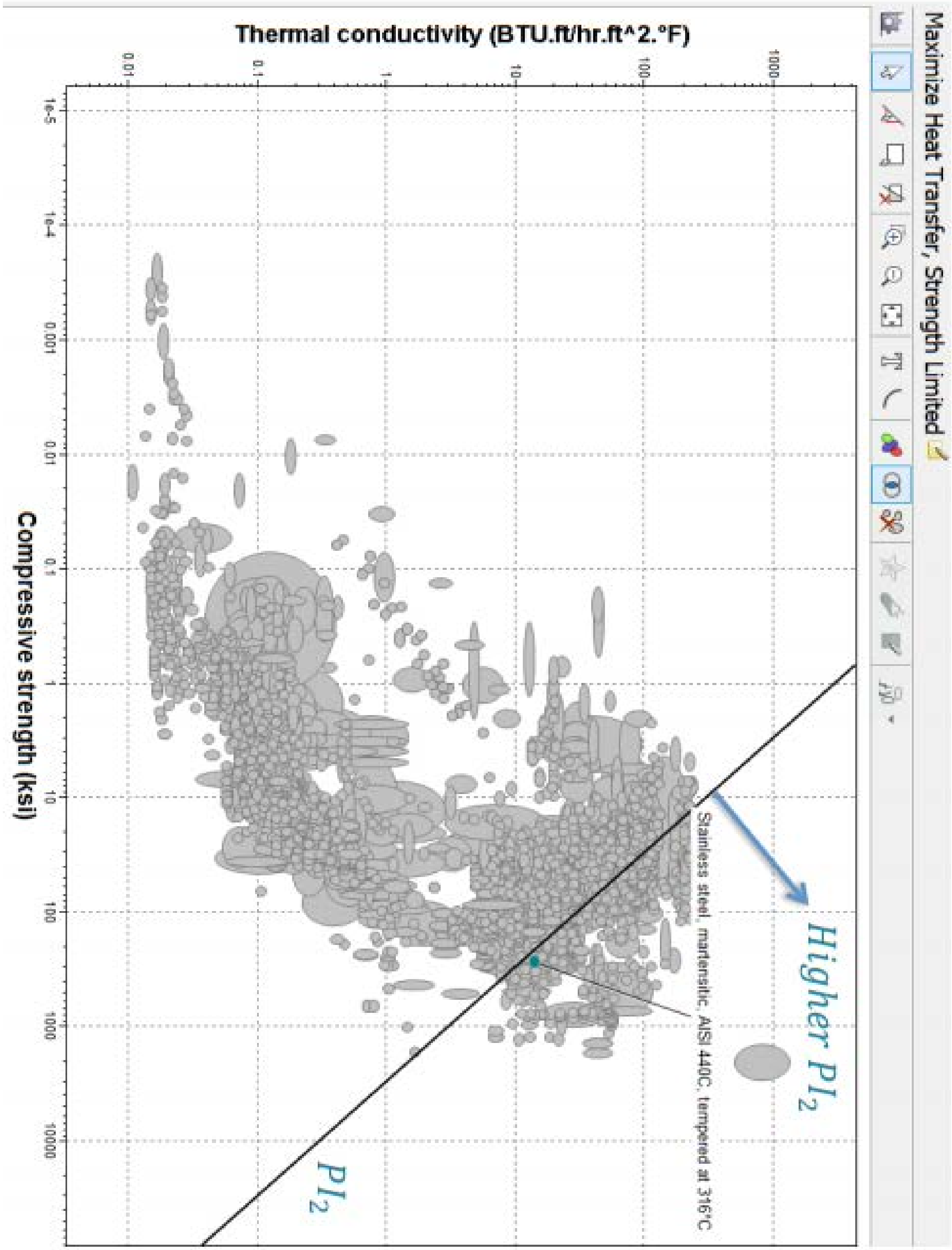


Figure 5M- Maximize Heat Transfer CES Graph

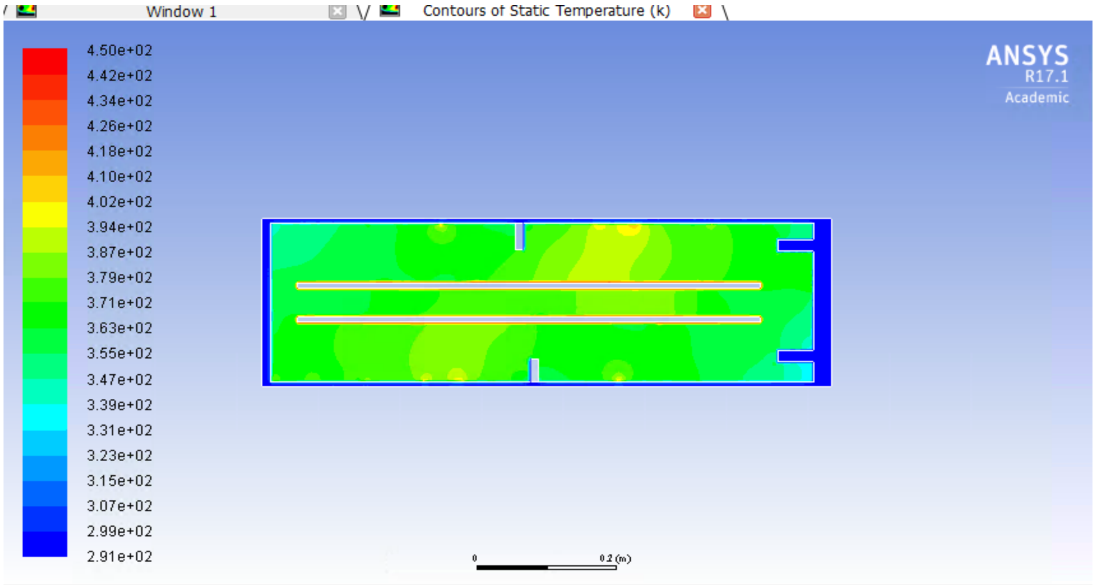


Figure 6M- Fluent Temperature Plot

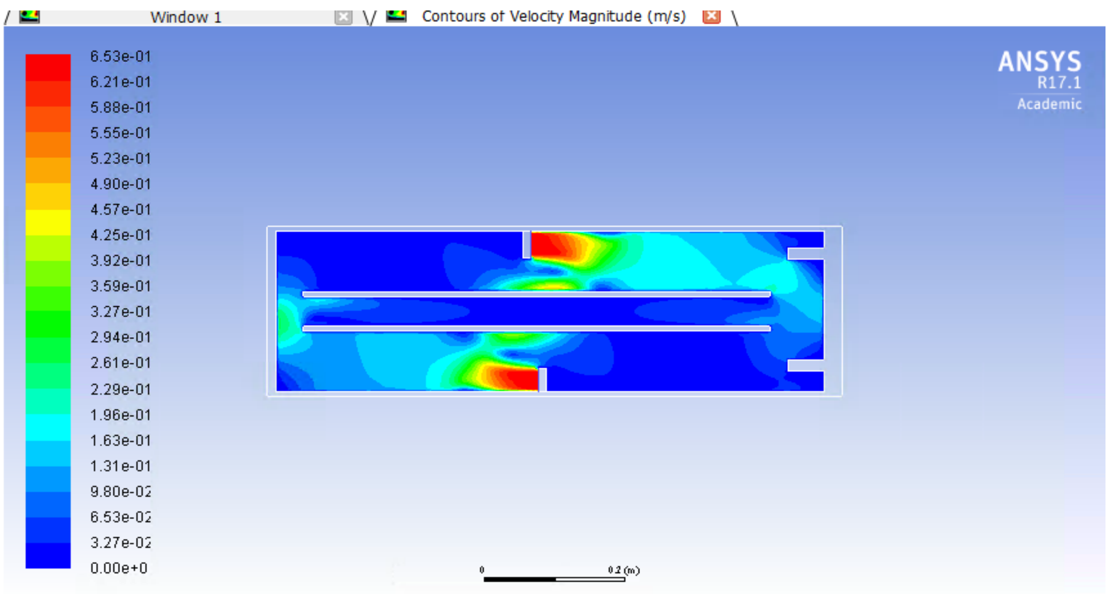


Figure 7M- Fluent Vector Plot

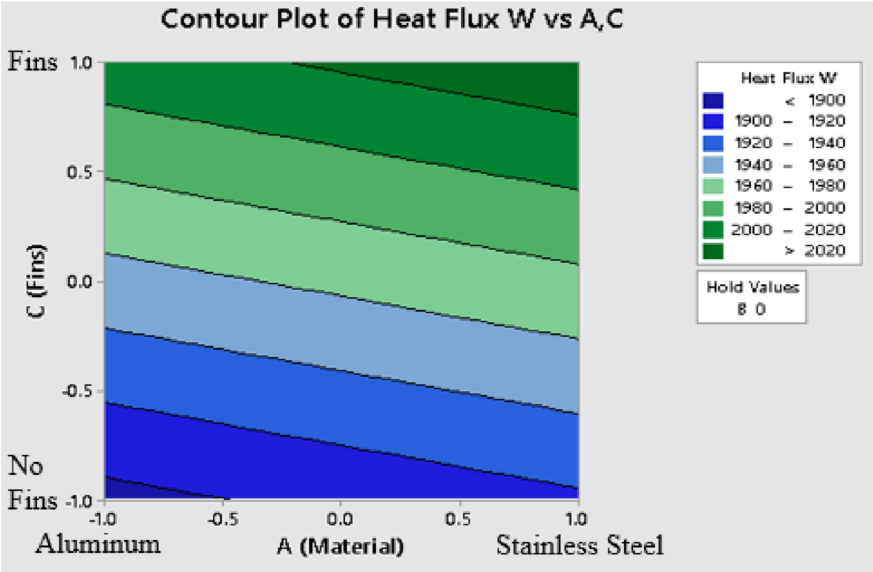


Figure 8M- Minitab Response Surface

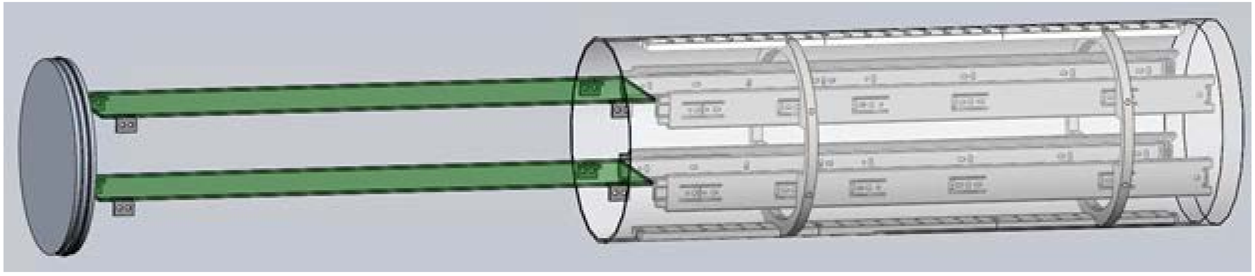


Figure 9M- Housing Drawer Design

Figure 10M- 3D Printed Bracket Rail

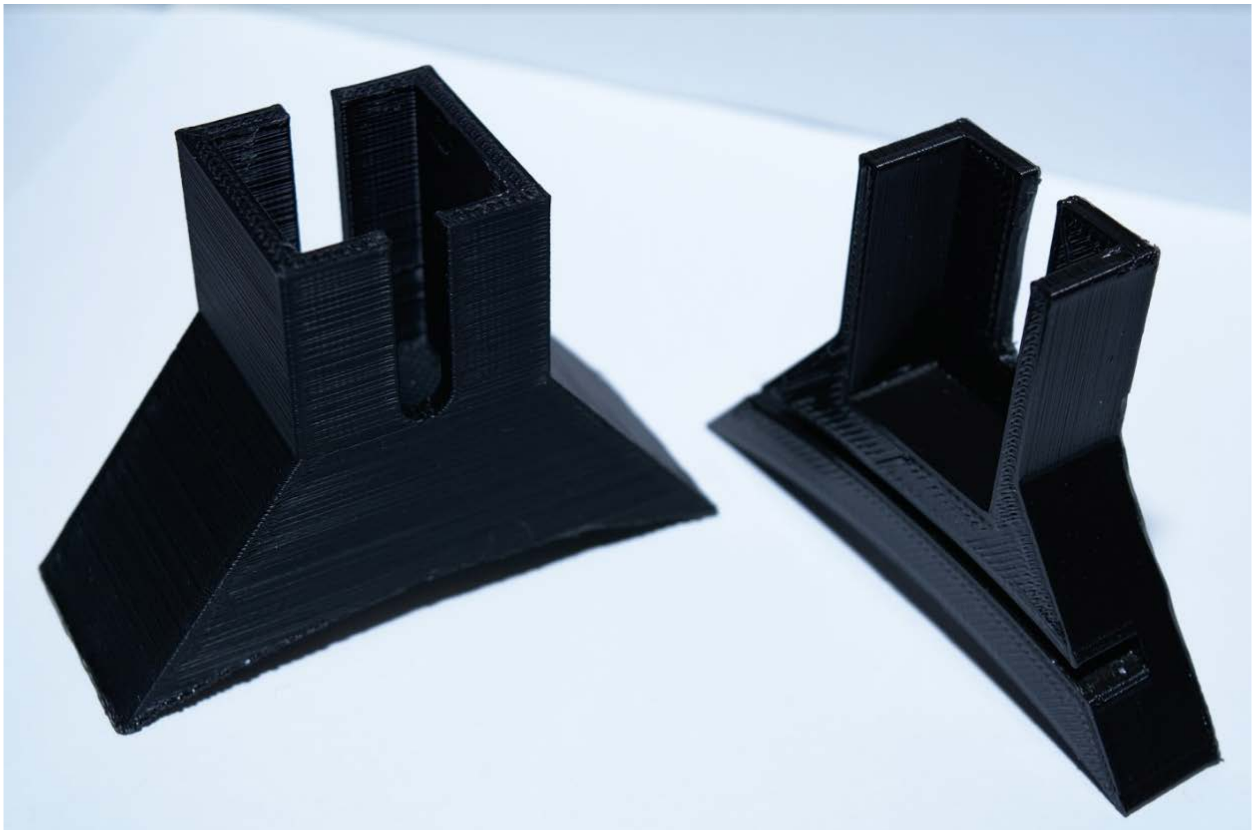


Figure 11M- 3D Printed Housing Clamps

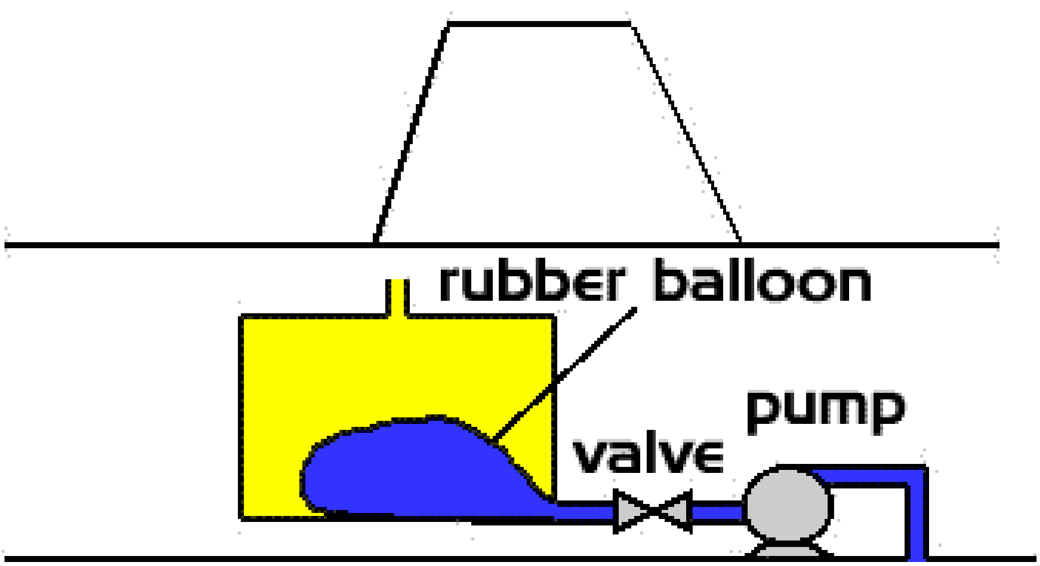


Figure 12M- Flexible Ballast Design

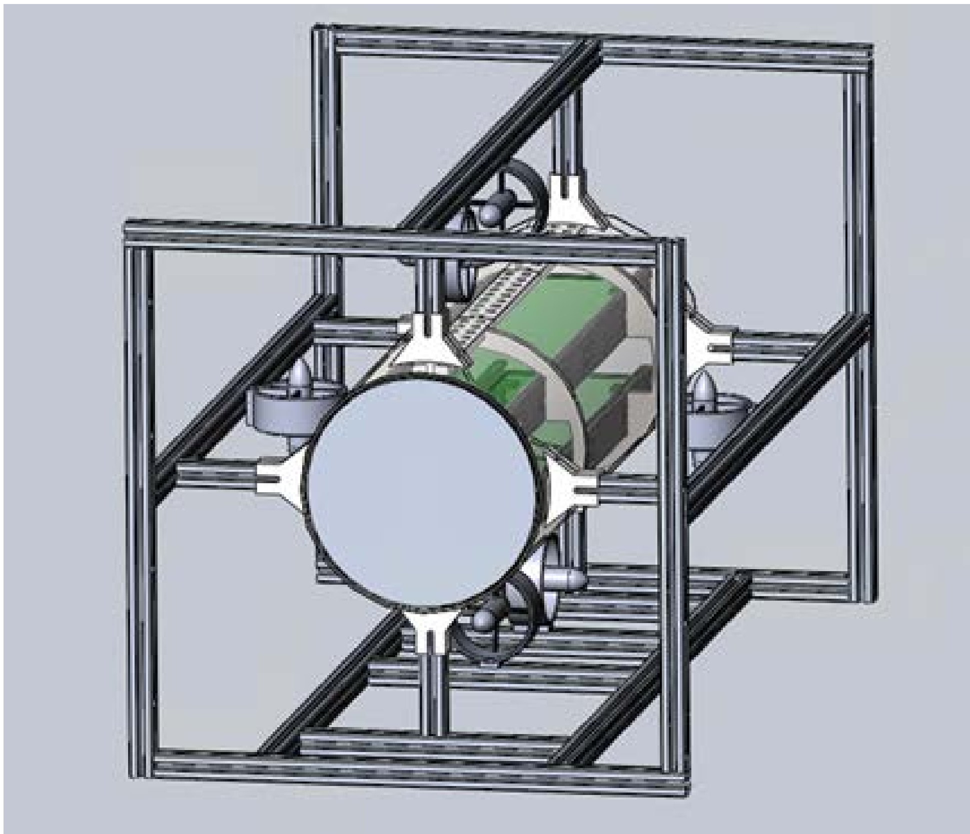


Figure 13M- Full CAD Image

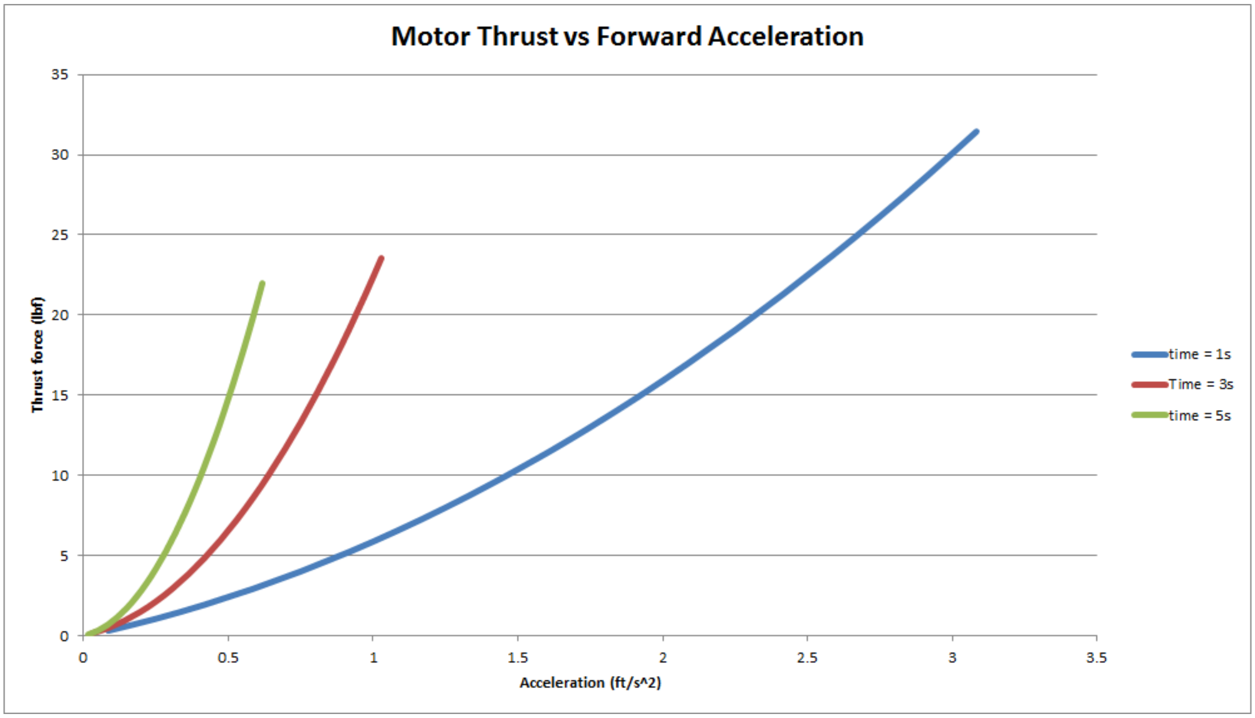


Figure 14M- Motor Thrust at Different Accelerations

<u>Appendix F – Power and Propulsion Figures</u>

Figure 1P: TMotor 3 Phase BLDC; 1.5in x 1.5 in

Figure 2P: MaxxAmps 8000 mAh LiPo battery; 1.5in x 5.5 in x 1 in ; 1.6 lb.

Figure 3P:Blue ESC 40 A ; 2in x 1in; 1 oz.

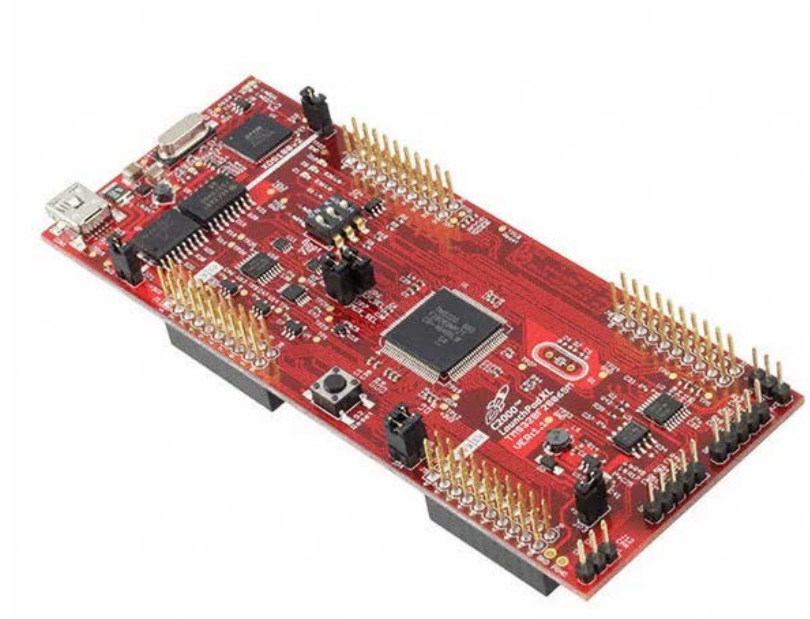


Figure 4P: Ti C2000 Delfino on LaunchPadXL Development Board; 2in x 5 in

Appendix G – Sensor Figures

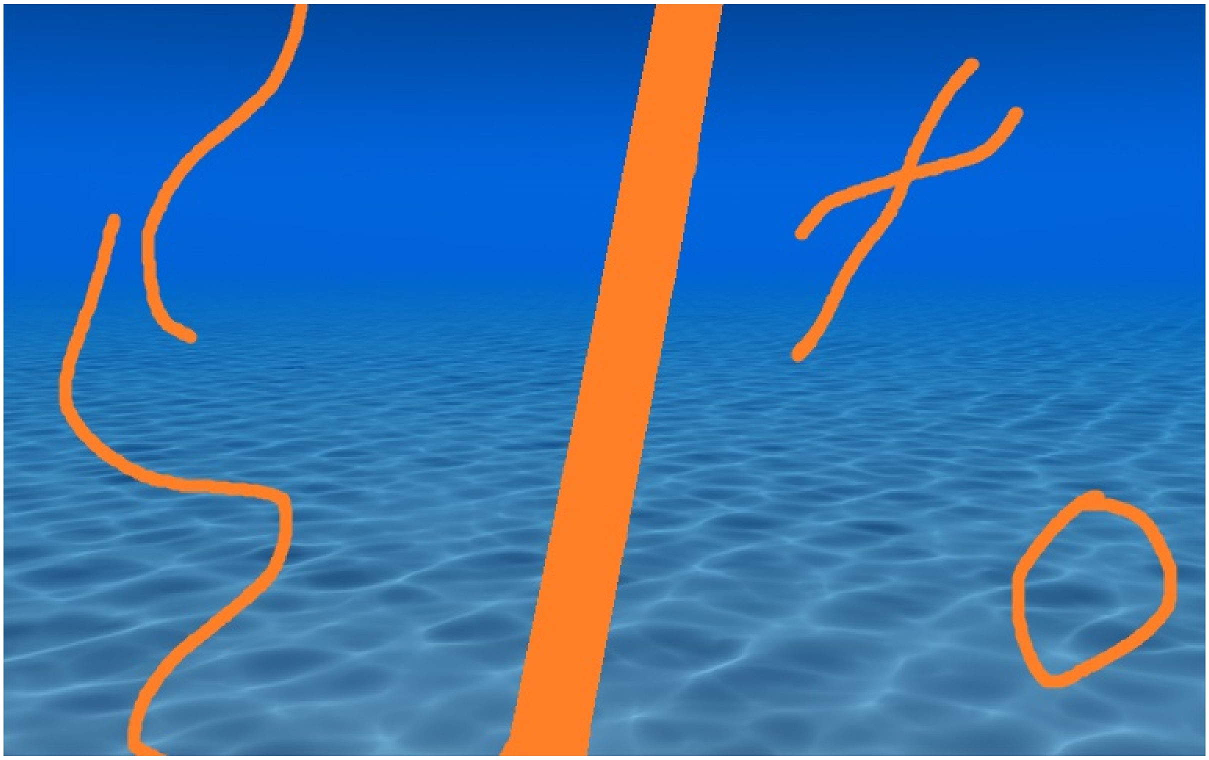


Figure 5: Test Image 1

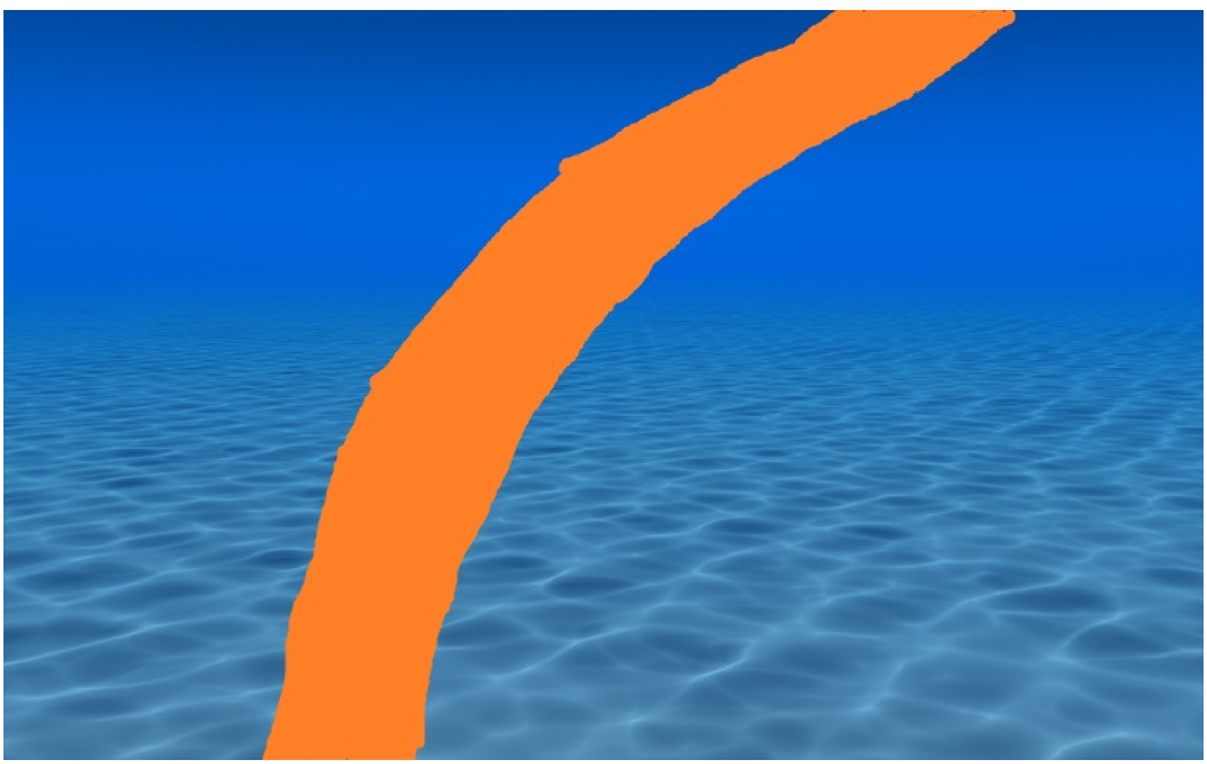


Figure 6: Test Image 2

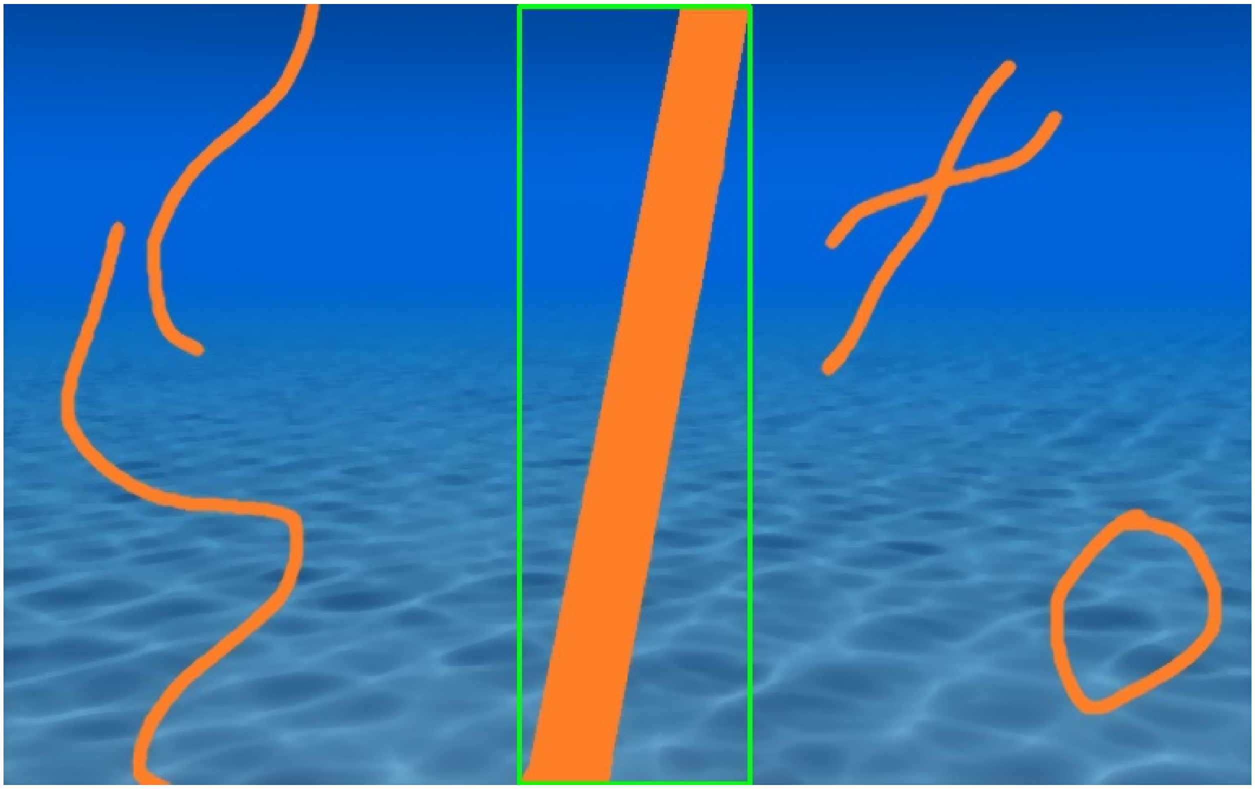


Figure 7: ROI Identified for Test Image 1

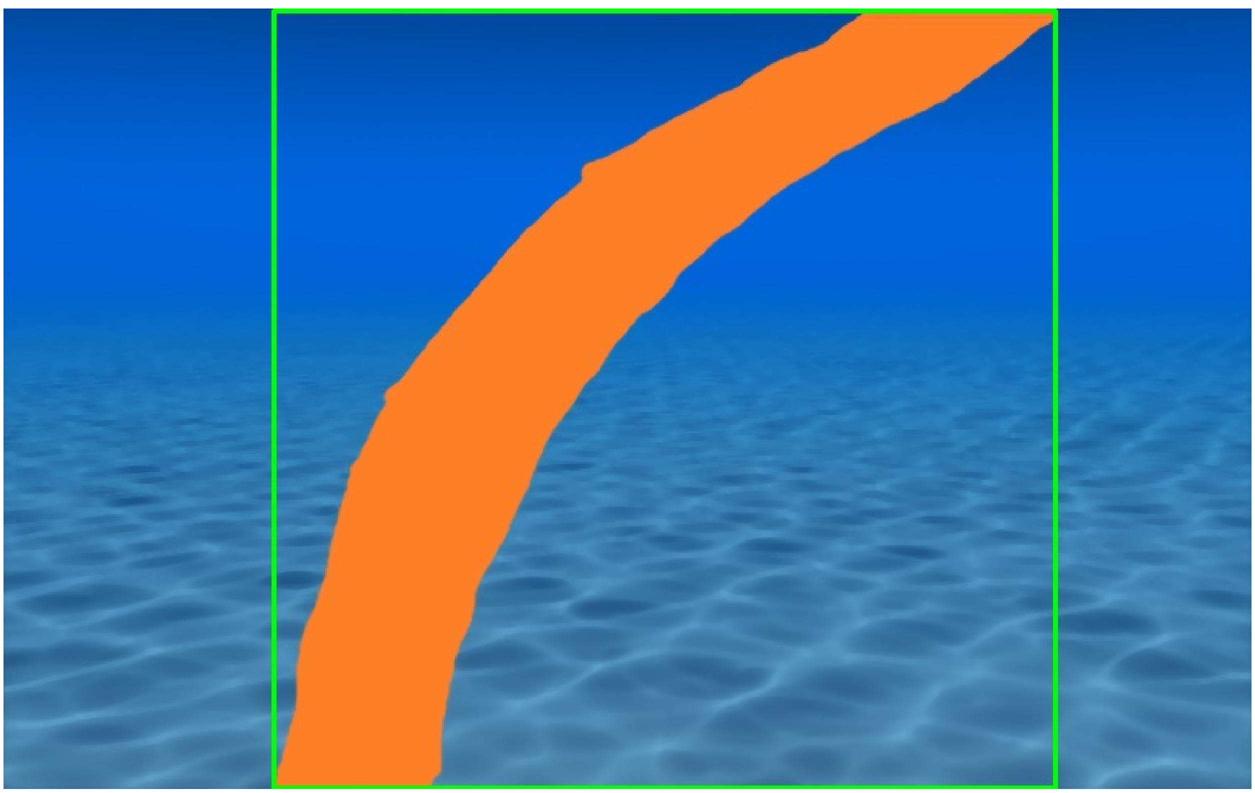


Figure 8: ROI Identified for Test Image 2

Figure 9: Final Filtering of Test Image 1

Figure 10: Final Filtering of Test Image 2

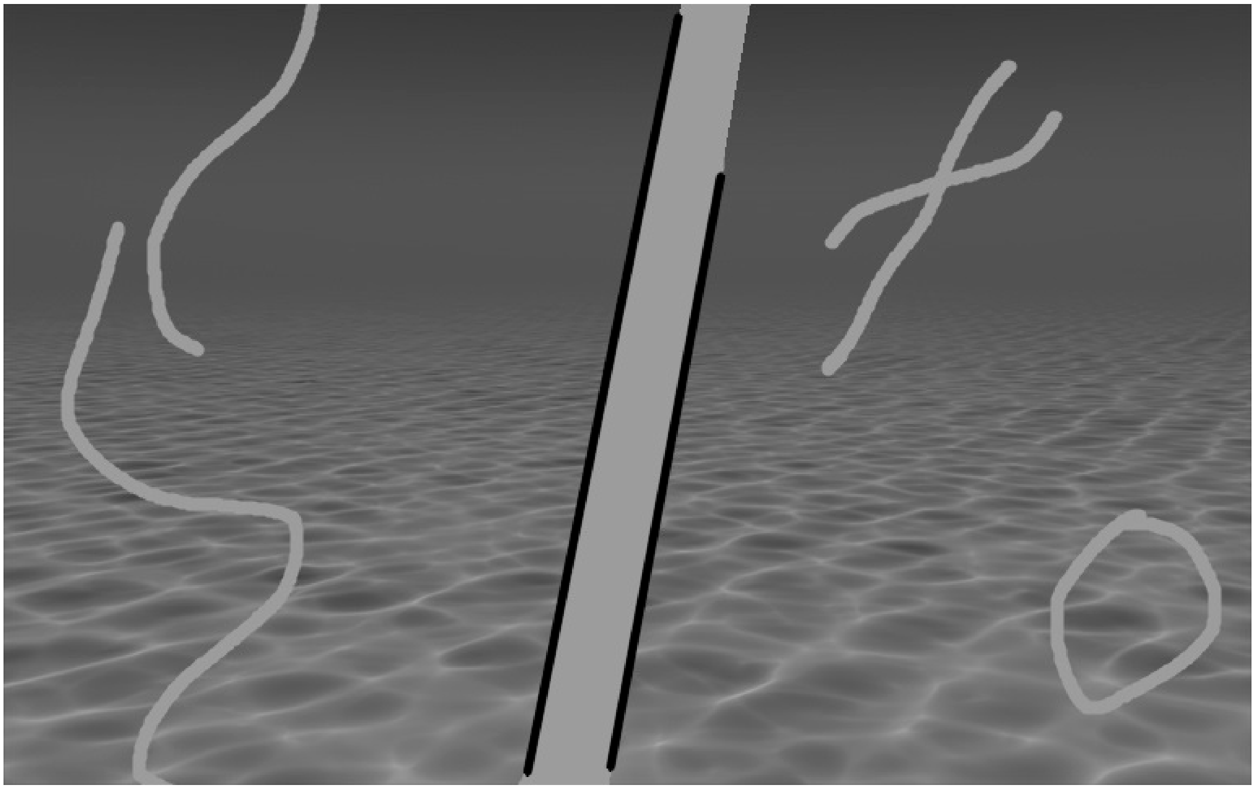


Figure 11: Filtering Attempt #1 Test Image 1

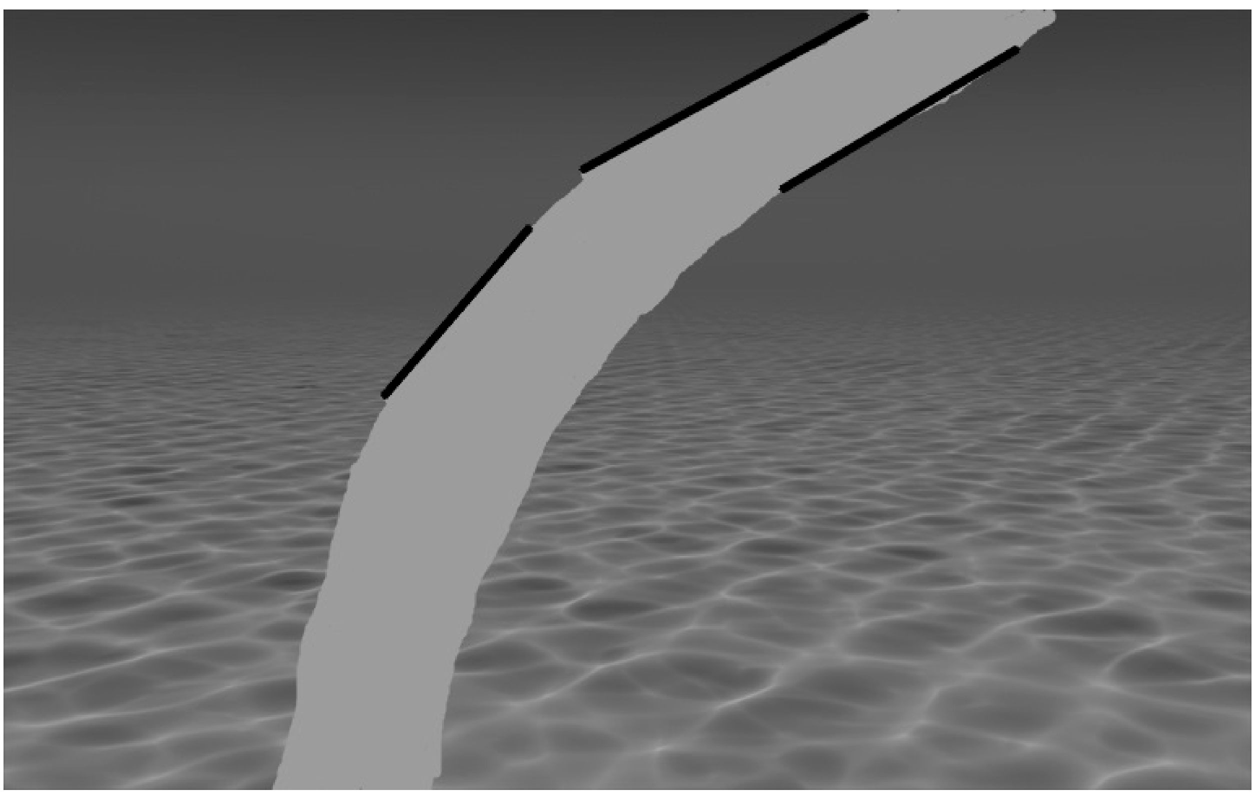


Figure 12: Filtering Attempt #1 Test Image 2

Figure 13: Skeleton Test Image 1

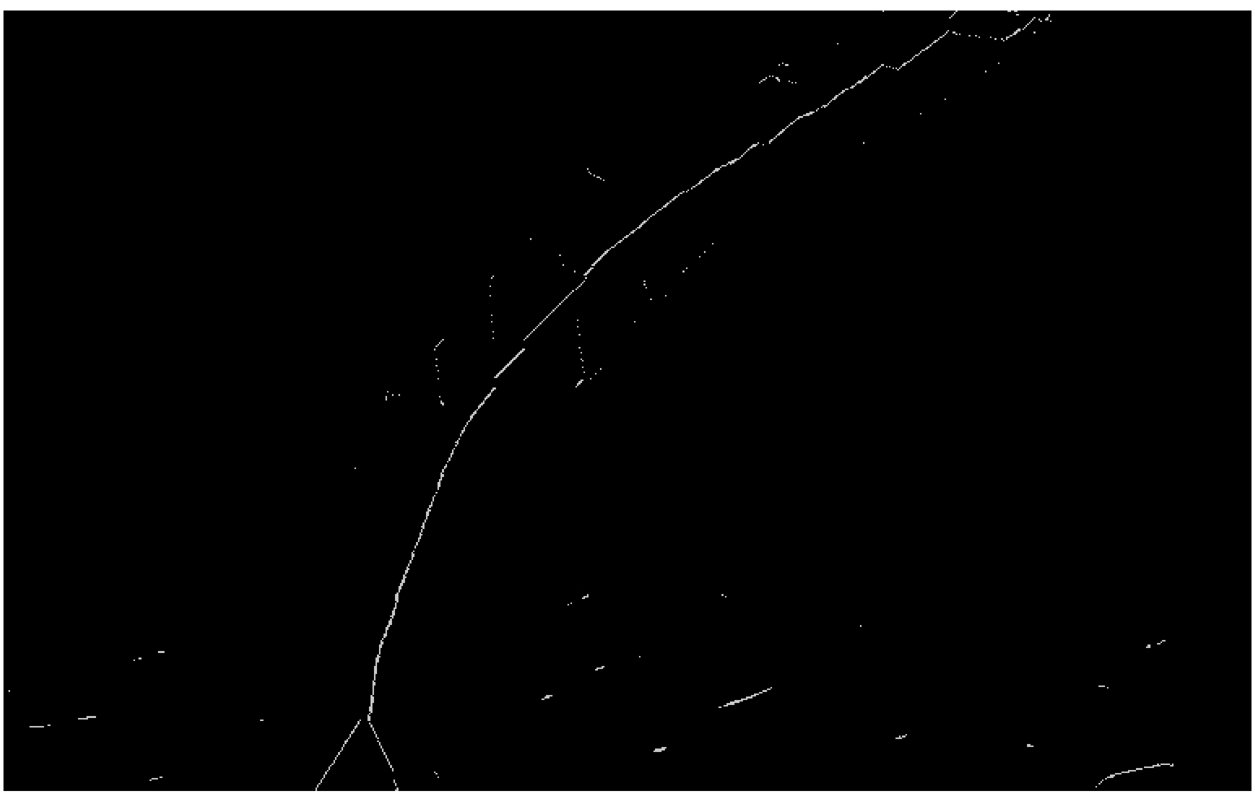


Figure 14: Skeleton Test Image 2

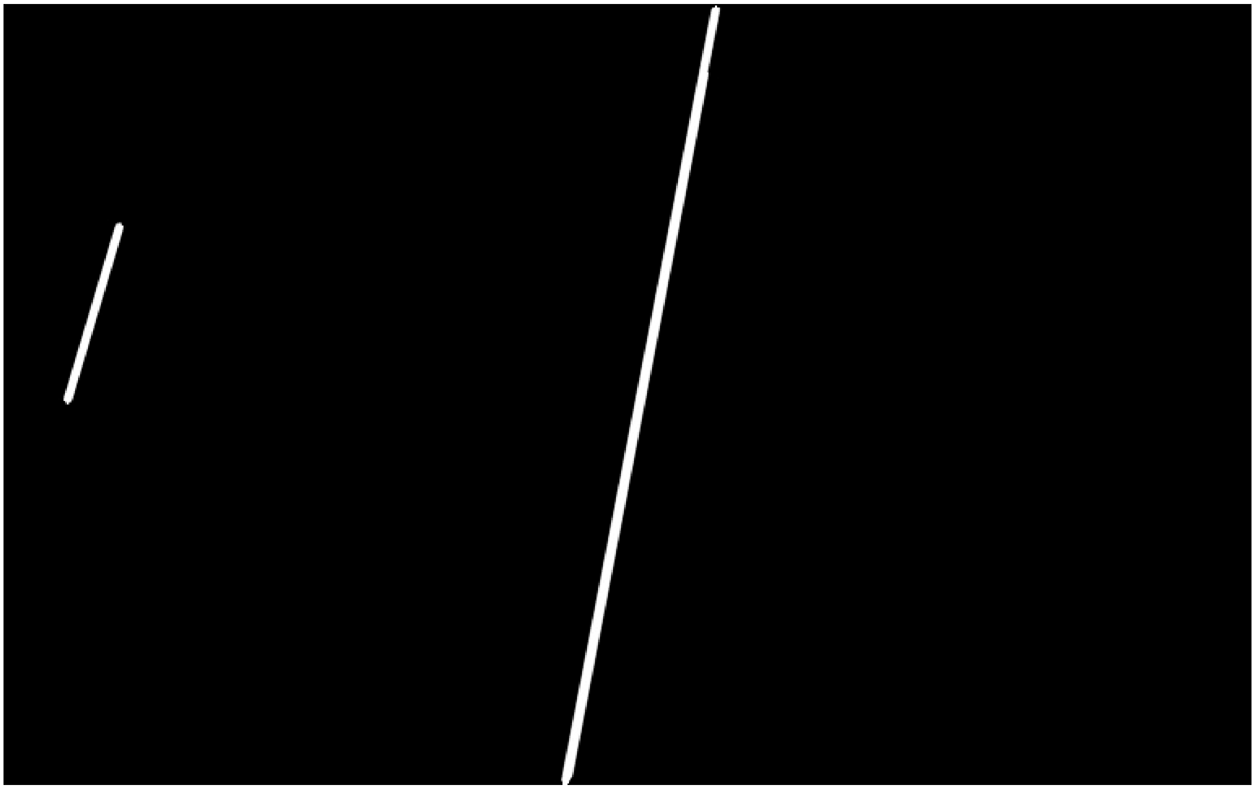


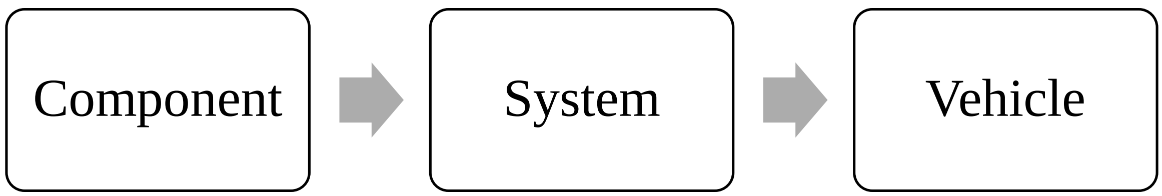
Figure 15: Filtering Attempt #2 Test Image 1

Figure 16: Filtering Attempt #2 Test Image 2

Appendix H – Device Test, Validation, & Characterization (DTVC)

DTVC Structure

Structure for the DTVC is a three “test gate” system:



How this works

1. We each start with our respective sub-team component level stuff and run through the steps listed on the next page.

2. Then take the component level and integrate all the components into your respective sub-team system, and again go through the same steps.

3. Once that has all been done, we can then take all three sub-team systems and integrate them all into the vehicle. This step still follows the exact same steps as before.

How to use these steps

1. Take gate and apply metrics.

2. Come up with tests for all the material tests.

3. Come up with tests for the required spec of the gate.

4. Take all the tests you have come up with and run them through the Test Screener.

5. If a test fails then try to come up with a work around, if not possible then we have to forsake that test.

Testing Criteria

At each of the gates we ask the following questions about how to satisfy our metrics.

* All metrics are performance metrics as well as the testing metrics*

Metric A: Efficiency-

Can you change your response for changing environment?

Metric B: Endurance-

How long (time, distance, whatever metric is pertinent) can you do what you were designed to do?

All tests must satisfy both metric A and B:

1) Material Tests
    - External and Internal Event Tests
        i. Humidity
        ii. Pressure
        iii. 0 to 100% (0 = Dry and 100% = Wet)
        iv. Ambient temperature
        v. Medium changes
        vi. Durability Characteristics
2) Perform-desired-function- test

Test Screener

- Meta Test Metrics
- Duration back to original state
    - How quickly can I test?
- Cost
    - Can we afford effective testing?
- Time
    - Can we begin and finish testing in a realistic amount of time?
- Location
    - Where can we test?
- Repeatability
    - Can I do it exactly the same every time?

DTVC Overview

Last Edited By: Tyler Loughrey

Date: 11/30/16

I. Mechanical Overview

a. Component
b. System
c. Vehicle

II. Electrical Overview

a. Sensor
   i. Component
   ii. System
   iii. Vehicle

b. Propulsion
   i. Component
   ii. System
   iii. Vehicle

Date: 10/25/2017

Modified: 10/25/2017

Team: Mechanical

Gate: Component

a) **Material Test**
   i) Chassis
      (1) Impact test (Metric A)
         (a) Says that chassis maintains original shape
      (2) Fatigue test (Metric B).
         (a) Says if chassis can withstand multiple impacts
      (3) Corrosion test (Metric A B)
         (a) Says if corrosion will occur on chassis
      (4) Loading test dry land (Metric A B)
         (a) Says if chassis can withstand max load of vessel
   ii) Electrical Housing
      (1) Water proof timed test (Metric B)
         (a) Says if housing maintains dry environment
      (2) Water proof depth test (Metric A B)
         (a) Says if housing maintains dry environment
      (3) Heat dissipation (Metric A B)
         (a) Says if housing reaches and maintains appropriate operating temperature
      (4) Deformation test (Metric A)
         (a) Says if electrical housing plastically deforms under applied heat
   iii) Fail Safe
      (1) Valve actuation test (Metric A)
         (a) Says if valve actuates upon electrical loss
      (2) Mass release test (Metric A)
         (a) Says if mass is released upon valve actuation
      (3) Inflation test

(a) Says if ‘balloon’ inflates and stays inflated (Metric A B)

iv) Clamps

(1) Impact test (Metric A)

(a) Says if the clamps can withstand the applied impact load

(2) Loading test dry land (Metric A B)

(a) Says if the clamps can withstand the weight of housing for specified time

(3) Loading test water (Metric A B)

(a) Says if the clamps can withstand the weight of housing for specified time

Date: 10/26/2017

Modified: 11/30/2016

Team: Sensors

Gate: Component

1) Material Test

- a) External Tests
  - i) IMU
    - (1) Static vs. Dynamic Temperature Test (Metric A, B)
      - (a) Static
        - (i) Underwater as sole running unit
      - (b) Dynamic
        - (i) Underwater with all other units running simultaneously
  - ii) Pressure Transducers
    - (1) Water suitability (Metric B)
      - (a) Says if transducers operate correctly in water; watertight.
    - (2) Temperature Test (Metric A, B)
      - (a) Submerged in water
  - iii) Cameras
    - (1) Manufacturer's Specifications Test (Metric A)
      - (a) Says if cameras meet Manufacturer's Specifications
    - (2) Static vs. Dynamic Temperature Test (Metric A, B)
      - (a) Static
        - (i) Underwater as sole running unit
      - (b) Dynamic
        - (i) Underwater with all other units running simultaneously
  - iv) Sensor Processing Unit (Metric A)
    - (1) Says if it boots
    - (2) Says if outputs are within expected range
- b) Internal Tests
  - i) IMU

(1) Manufacturer's Specifications Test (Metric A)

(a) Says if IMU meets Manufacturer's Specifications

(2) Communication Test (Metric A)

(a) Says if information can be retrieved

(b) With motion input, says if it gives representative output

ii) Pressure Transducers

(1) Manufacturer's Specifications Test (Metric A)

(a) Says if transducers meet Manufacturer's Specifications

(2) Load Characterization (Metric A)

(a) Voltage/Amperage/Power characterization

(3) Output Test (Metric A)

(a) Says if a voltage within expected range is output

iii) Cameras

(1) Manufacturer's Specifications Test (Metric A)

(a) Says if cameras meet Manufacturer's Specifications

(2) Communication Test (Metric A)

(a) Says if information can be retrieved

iv) Sensor Processing Unit (Metric A)

(1) Heat up test

(2) Manufacturer's Specifications Test

(a) Says if SPU meets Manufacturer's Specifications

2) Perform-Desired-Function Testing

a) IMU

i) Calibration test (Metric A)

(1) Says if IMU gives accurate movement output

ii) Software Testing (Metric A)

(1) Says if software handles any expected and unexpected output from IMU

(2) Says if software handles calculations correctly

b) Pressure Transducers

i) Calibration test (Metric A)

(1) Says if transducers give accurate pressure change

ii) Software Testing (Metric A)

(1) Says if software handles any expected and unexpected voltage from transducers

(2) Says if software handles calculations correctly

c) Cameras

i) Software Testing (Metric A)

(1) Says if software handles any expected and unexpected image from cameras

(2) Says if software handles image manipulation correctly

d) Sensor Processing Unit

i) Software Testing (Metric A)

(1) Says if software handles all inputs from sensors

(2) Says if software ignores or handles bad inputs

(3) Says if software calculates meaningful data

ii) Stress Testing (Metric B)

(1) Measure change in temperature, voltage, and current

Date: 10/24/2017

Modified: 10/28/2017

Team: Propulsion

Gate: Component

1) **Material Test**
    a) External Test
        i) Motors
            (1) Spin/Bump test (Metric A)
                (a) Says if motor runs
            (2) Water suitability (Metric B)
                (a) Says if motor runs in water; watertight
            (3) Manufacturer's Specifications Test (Metric A)
                (a) Does motor meet Manufacturer's Specifications?
            (4) Load characterization (Metric A)
                (a) Volt/Amp/Power characterization
            (5) Static vs. Dynamic Temperature Test
                (a) Dynamic (Metric A,B)
                    (i) Large body with motion (in water) of motor under varying voltage/current conditions
                (b) Static (Metric A,B)
                    (i) Small body without motion of motor underwater varying voltage and current conditions
    b) Internal Tests
        i) Battery (as naked cells)
            (1) Load Characterization (Metric A)
                (a) High resistance load test to get loading current
            (2) Temperature Test (Metric A)
                (a) How much heat up under 10%, 20%, … 100% load
        ii) BMS

(1) Communication Test (Metric A)

(a) Does it talk?

(b) Can it be talked to?

iii) ESC (Metric A)

(1) With input, does it give a representative output?

(2) Heat up test

(a) How much heat up under 10%, 20%, … 100% load

(i) Don't really need, but it would be nice…

iv) MPU (Metric A)

(1) Does it boot?

(2) Can we flash it?

(3) Does output work?

(4) Heat up test

(a) How much heat up under 10%, 20%, … 100% load

(5) Power drop

v) HFD (Metric A)

(1) Does it meet Manufacturer Specifications?

(2) Does it actuate?

vi) EFD (Metric A)

(1) Does it meet Manufacturer Specifications?

vii) Cabling and Connectors (Metric B)

(1) Is conductor insulation electrically sound?

(2) Do connectors suit/fit the conductor number/size?

viii) MCU (Metric A)

(1) Does it boot?

(2) Can we flash it?

(3) Does output work?

(4) Heat up test

(a) How much heat up under 10%, 20%, … 100% load

(5) Power drop

2) **Perform-desired-function testing**
   a) Motors – MPU (Metric A)
      i) Motion Test
         (1) Does it go forward, backward, and braking?
      ii) Coordination Test
         (1) Do motors give coordinated response?
            (a) i.e. we say left and we move left
      iii) Stress Testing (Metric B)
         (1) Pulse motors forward and backward till something happens
         (2) Measure delta temperature, voltage, and current
         (3) Want to model the worst random walk ever
   b) MPU
         (1) State test
            (a) Has X distinct states for position and that maps to X distinct motor states.
            (b) Confirms no dead states
   c) HFD/EFD
         (1) Test switching via push button (Emergency Disconnect)
         (2) Timed software based failure (Software generated fault)

DTVC Expected Testing Outcomes

Last Edited By: Phil Meister

Date: 10/28/16

III. Mechanical Overview

a. Component
b. System
c. Vehicle

IV. Electrical Overview

a. Sensor
   i. Component
   ii. System
   iii. Vehicle

b. Propulsion
   i. Component
   ii. System
   iii. Vehicle

Date: 10/25/2017

Modified: 10/28/2017

Team: Mechanical

Gate: Component

1) **Material Test**
   a) Chassis
      i) Impact test (Metric A)
         (1) Chassis will withstand a collision traveling at 0.508 m/s
      ii) Fatigue test (Metric B)
         (1) Chassis will be able to withstand 20 impacts @ .508 m/s
      iii) Corrosion test (Metric A B)
         (1) Chassis will not corrode from H20 and Air interaction over 1 year
         (2) Chassis will not corrode from weak chlorine
         (3) Chassis will not corrode in salt water
      iv) Loading test dry land (Metric A B)
         (1) The chassis will withstand a weight of 125 lbs
   b) Electrical Housing
      i) Water proof timed test (Metric B)
         (1) Will be water tight for 1 hour of continuous immersion in water
      ii) Heat dissipation (Metric A B)
         (1) The EH will maintain a temperature below the maximum electrical operating temperature
   c) Fail Safe
      i) Valve actuation test (Metric A)
         (1) The fail safe valve will actuate upon electrical failure
      ii) Mass release test (Metric A)
         (1) The mass will release upon valve actuation
   d) Clamps
      i) Loading test dry land (Metric A B)

(a) The clamps will withstand a weight of 125 lbs

Date: 10/26/2017

Modified: 10/26/2017

Team: Sensors

Gate: Component

1) **Material Test**
   a) External Tests
      i) IMU
         (1) Static vs. Dynamic Temperature Test (Metric A, B)
            (a) Static
               (i) Underwater as sole running unit, IMU will not heat over 3^{o}C over long periods of time (>30 minutes)
            (b) Dynamic
               (i) Underwater with all other units running simultaneously, IMU will not heat over 3^{o}C over long periods of time (>30 minutes)
      ii) Pressure Transducers
         (1) Water suitability (Metric B)
            (a) Transducer will only have water on pressure sensor.
            (b) Transducer will operate underwater for >30 minutes.
         (2) Temperature Test (Metric A, B)
            (a) Transducers will not heat up over long or short term use (>30 minutes)
      iii) Cameras
         (1) Static vs. Dynamic Temperature Test (Metric A, B)
            (a) Static
               (i) Underwater as sole running unit, cameras should not heat over 3^{o}C over long periods of time (>30 minutes)
            (b) Dynamic
               (i) Underwater with all other units running simultaneously, cameras should not heat over 3^{o}C over long periods of time (>30 minutes)
      iv) Sensor Processing Unit (Metric A)

(1) Will boot.

(2) Output can be measured using oscilloscope or test rig.

b) Internal Tests

i) IMU

(1) Manufacturer's Specifications Test (Metric A)

(a) IMU will have accuracy and noise characteristics of manufacturer's specs.

(2) Communication Test (Metric A)

(a) Communication will be one-way.

(b) Communications will be at least 90% reliable (1 in 10 signals fail)

ii) Pressure Transducers

(1) Manufacturer's Specifications Test (Metric A)

(a) Pressure Transducers will meet input and output voltage and current characteristics per manufacturer's specifications.

(2) Output Test (Metric A)

(a) Pressure Transducers will output a linear voltage based on current pressure.

iii) Cameras

(1) Manufacturer's Specifications Test (Metric A)

(a) Cameras will have the framerate and resolution of manufacturer's specs.

(2) Communication Test (Metric A)

(a) Communication will be one-way.

(b) Communications will be at least 90% reliable (1 in 10 signals fail)

iv) Sensor Processing Unit (Metric A)

(1) Will operate at near peak performance up to at least 100°C

(2) Manufacturer's Specifications Test

(a) SPU will meet processing characteristics of manufacturer's specs.

2) Perform-Desired-Function Testing

a) IMU

i) Calibration test (Metric A)

(1) IMU will be accurate within 5% of real movement.

ii) Software Testing (Metric A)

(1) Software will handle any expected or unexpected output from IMU.

(2) Software will calculate IMU data correctly.

b) Pressure Transducers

i) Calibration test (Metric A)

(1) Transducers will be accurate within 5% of real pressure.

ii) Software Testing (Metric A)

(1) Software will handle any expected or unexpected output from transducers.

(2) Software will calculate transducer output correctly.

c) Cameras

i) Software Testing (Metric A)

(1) Software will handle any expected or unexpected image from camera.

(2) Software will manipulate images correctly.

d) Sensor Processing Unit

i) Software Testing (Metric A)

(1) Software will handle all inputs from all sensors.

(2) Software will ignore bad inputs.

(3) Software will output meaningful data.

ii) Stress Testing (Metric B)

(1) Under full load, SPU will continue to operate.

Date: 10/24/2017

Modified: 10/24/2017

Team: Propulsion

Gate: Component

1) **Material Test**
   a) External Test
      i) Motors
         (1) Spin/Bump test (Metric A)
            (a) Motor will run unimpeded under manufactures voltage/amperage specs
         (2) Water suitability (Metric B)
            (a) Motor will have no water in it
            (b) Motor will run underwater for >30 minutes
         (3) Manufacturer's Specifications Test (Metric A)
            (a) Motor will not have the speed/voltage characteristics per manufactures specs
            (b) Motor will not have the torque/amperage characteristics per manufactures specs
         (4) Load characterization (Metric A)
            (a) Motor characterization will be with 10% of manufactures specs in voltage, amperage handling characteristics as well as thrust
         (5) Static vs. Dynamic Temperature Test
            (a) Dynamic (Metric A,B)
               (i) Motor will exhibit no heat up and perform as if "cold"
            (b) Static (Metric A,B)
               (i) Motor will exhibit heat up after substantially shorter time than in dynamic test
               (ii) Motor characteristics will degrade but not beyond the point of usability
   b) Internal Tests
      i) Battery (as naked cells)
         (1) Load Characterization (Metric A)

(a) Battery cells will exhibit poor performance (read as ability to respond) over 20 minutes

(b) Battery cells will be able to respond to all loads when fully charged

(c) Battery cells will drop no more than 1% in power output for each 1% load increase

(2) Temperature Test (Metric A)

(a) Battery cells will heat no more than 5 °C over long term use (>20 minutes)

(b) Battery cells will not heat up under short term use (< 10 minutes)

ii) BMS

(1) Communication Test (Metric A)

(a) Communication will be bi-directional

(b) Communication from controllers will disable batteries

(c) Communications will be at least 90% reliable (1 in 10 signals fail)

iii) ESC (Metric A)

(1) Voltage/Phase will have a 1-1 relationship with input signal

(2) Will heat up more under heavy load than light load

(3) Will handle rated amperage and voltage +10%

(4) Will have phase but not amplitude/switching issues upon heavy load

(5) Heat (within spec) will not cause any more than phase distortion

iv) MPU (Metric A)

(1) Will boot

(2) Will take at least 10,000 flashings (typical for solid-state)

(3) Output will be tested in hardware; actuated in software

(4) Power consumption will be no more than 700kJ for 30 minutes

(5) Will operate at near peak performance up to at least 100°C

v) HFD (Metric A)

(1) Will be within manufactures spec +/- 10%

(2) Will actuate 100% of the time

(3) Will break under rated load (measured in Amperes)

vi) EFD (Metric A)

(1) Will be within manufactures spec +/- 10%

(2) Will actuate 100% of the Will break under rated load (measured in Amperes)

vii) Cabling and Connectors (Metric B)

(1) Conductors will handle 1.5x times rated voltage

(2) Multi-conductors will not exhibit insulation failures

(3) Connectors will be chosen to physically and electrically fit conductors

2) Perform-desired-function testing

a) Motors – MPU (Metric A)

i) Motion Test

(1) Does it go forward, backward, and braking?

ii) Coordination Test

(1) Do motors give coordinated response?

(a) i.e. we say left and we move left

iii) Stress Testing (Metric B)

(1) Pulse motors forward and backward till something happens

(2) Measure delta temperature, voltage, and current

(3) Want to model the worst random walk ever

b) MPU

(1) State test

(a) Has X distinct states for position and that maps to X distinct motor states.

(b) Confirms no dead states

c) HFD/EFD

(1) Test switching via push button (Emergency Disconnect)

(2) Timed software based failure (Software generated fault)