University of Colorado
Department of Aerospace Engineering Sciences
Senior Projects - ASEN 4028

Yellow Europa Low-Level Oceanic Wandering Submarine
(YELLOW Submarine)

Project Final Report

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LOCKHEED MARTIN

Project Final Report

Senior Projects - ASEN 4028

Preamble

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List of Acronyms

AUV = Autonomous Underwater Vehicle
CB = Center of Buoyancy
CG = Center of Gravity
DOF = Degrees of Freedom
POI = Point(s) of Interest
ROV = Remotely Operated Vehicle
SBC = Single-Board Computer
CAD = Computer Aided Design
CAM = Computer Aided Machining
YELLOW Submarine = Yellow Europa Low-Level Oceanic Wandering Submarine
YOLACT = You Only Look At CoefficienTs

Nomenclature

$\dot{Q}$ Heat Transfer Rate $W/m-K$

μ Coefficient of Friction $-$

ω Rotation Speed m/s

ρ Density kg/m^3

σ Stress MPa

A Area m^2

D Diameter m

F Force N

g Gravity m/s^2

h Heat Transfer Coefficient $W/m-K$ or Height m

k Thermal Conductivity $W/m-K$

L Housing Thickness m

m	Mass kg
N	Normal Force N
P	Pressure Pa
r	Radius m
S	Area m^2
T	Temperature K
t	Time t
V	Velocity m/s
z	Depth m

1. Project Purpose

Micah Zhang, Jacob Siegel

The primary mission of the YELLOW Submarine team is to create an autonomous, submersible vehicle capable of exploring a body of water with a volume of up to 50 x 25 x 3.65 meters. While performing its navigation, the AUV will be searching for and recording points of interest within the environment. The vehicle must do so with no input from an external source besides five minute uplink and downlink periods, which are situated in between twenty minute exploration periods. Prior to the uplink and downlink periods, the vehicle will surface and connect to the ground station located beside the test environment to begin the data transfer. The end goal of this project is to demonstrate that a mission to explore the ocean beneath the icy surface of Europa is feasible with current technology. To test the functionality of this AUV, it will be dropped into a mostly still pool of water and will explore and take data of that environment. Despite the fact that this will only be tested in a pool, how well it would operate under the conditions on Europa must be considered. In the context of this project, the vehicle will be communicating with a ground station near the exploration environment, however, for a conceptual deployment of this AUV on Europa, it would communicate with a satellite orbiting Europa.

It is important to emphasize that while it's true that the customer does plan to eventually send an AUV to Europa for exploration, the design being built by our team in the Spring will be used only as a technology demonstrator or prototype that will only be used in a swimming pool environment.

The novelty in our project comes from our use of an instance-segmentation based underwater navigation algorithm. This means that for our image processing stack the team will be using a stereo-depth camera in conjunction with the YOLACT real-time instance segmentation neural network architecture in order to provide the AUV with a sense of spatial-awareness as well as allow it to identify points of interest (POI). Then, the output of the image processing stack will be converted into commands for our control system via a state machine, the end result being the ability to search for and translate towards multiple POI within the swimming pool.

There are 3 primary benefits to using an instance segmentation-based underwater navigation algorithm provides over a traditional SLAM (simultaneous localization and mapping) algorithm. 1st, an instance segmentation-based underwater navigation algorithm does not require the AUV to have precise localization and tracking capabilities, an important consideration given that GPS does not work underwater. 2nd, an instance segmentation-based underwater navigation algorithm reduces the amount of time needed to complete the mission because unlike a traditional SLAM algorithm, the AUV does not need to first translate around the perimeter of the pool before moving towards each POI. 3rd, using an instance segmentation-based underwater navigation algorithm requires only a single stereo-depth camera and a powerful single-board computer as compared to SLAM, which would require multiple sonar-sensors as well as powerful single-board computer, sonar sensors typically being considerably more expensive than stereo-depth cameras.

Currently, there isn't any existing literature (academic papers) on combining real-time instance segmentation and stereo depth for AUV navigation. Furthermore, YOLACT is a new architecture, having just been published earlier this year (April 4th, 2019), and thus has not yet permeated into industry. This means that the successful demonstration of this project can both validate the YOLACT architecture to our customer for future use on their autonomous systems as well as introduce a new low-cost autonomous navigation methodology into the AUV community.

2. Project Objectives and Functional Requirements

Forrest Barnes, Benjamin Bruce, Colin Claytor, Griffith Kull, Christian Mitchell, Matthew Ryan, Micah Zhang

The functional block diagram (Fig. 1) shows the major elements of the AUV and how they interact to solve the problem. The voltages and data types/rates are also indicated where necessary. The power subsystem contains a battery, kill switch, and a PCB for regulating and distributing power to all necessary electrical components. The single board computer performs the object detection, makes navigation decisions, sends commands to the Pixhawk, and manages overall mission timing. The Pixhawk acts as an autopilot that receives commands from the computer and determines how the motors need to be controlled to carry out those commands. Sensor data is logged and stored for downlink during the communication windows. The ground station is composed of a laptop and Wi-Fi transmitter and receiver for uplink and downlink during communication windows.

The CONOPS (Fig. 2) shows a general outline of what tasks the AUV will perform in the pool environment and is split into 3 phases. Phase 1 will begin with a preparation period lasting no more than 15 minutes wherein the team will secure all of the electronic components inside the AUV, secure all connections, perform any other needed assembly,

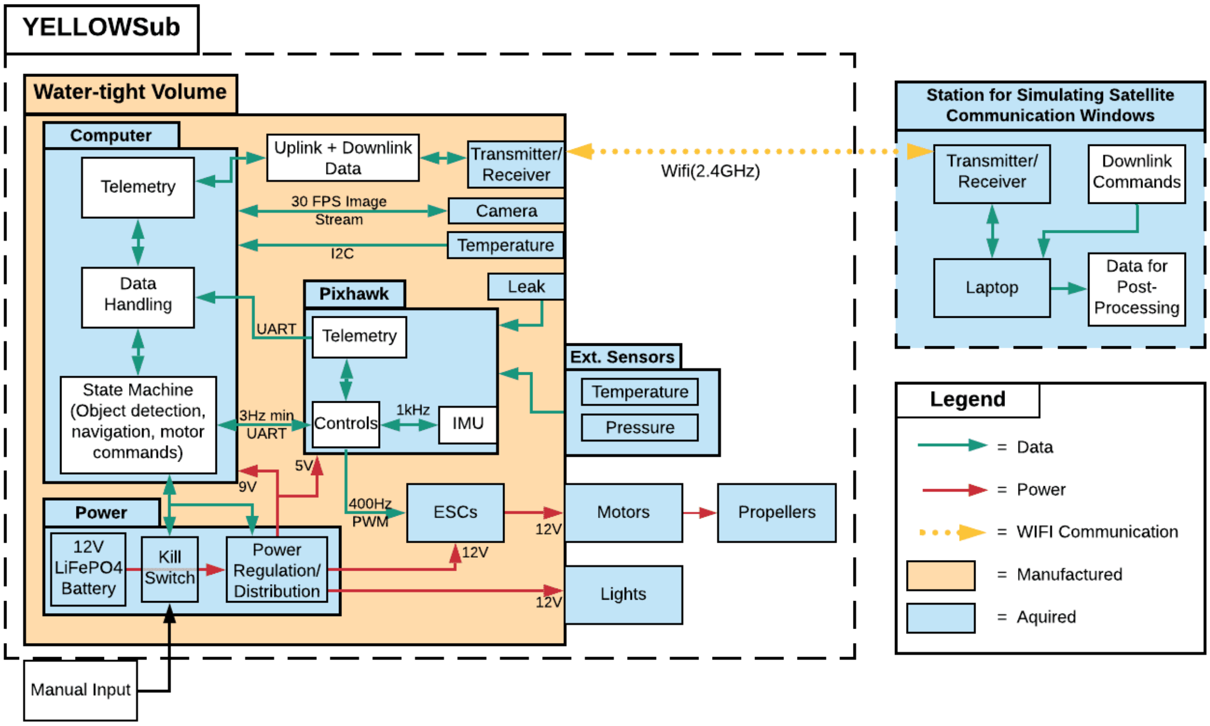

Figure 1: Functional Block Diagram

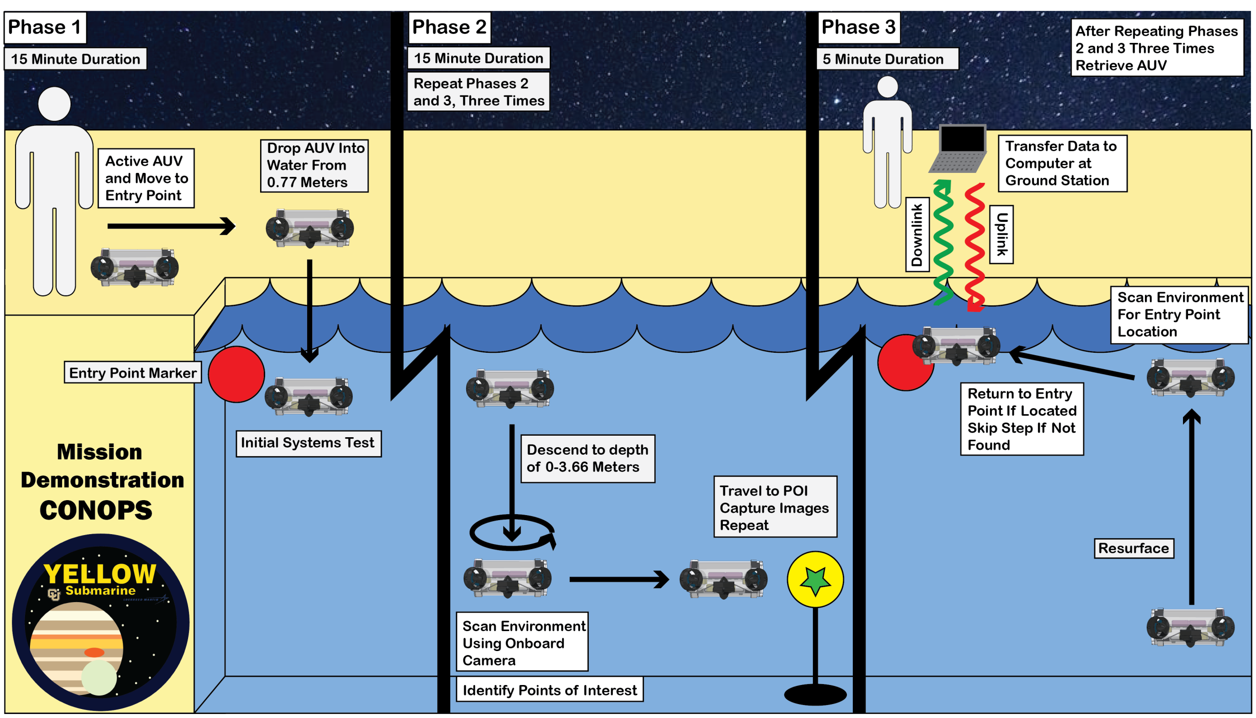

Figure 2: CONOPS

and then seal the back plate before turning it on. At that point, the AUV will be carried to the edge of the CU Rec Center dive well where it will be dropped into the water from 0.77m above the surface. The team will also secure a fully submerged drop point marker at the drop location. Once on the surface of the water, the AUV will perform an initial self-check to ensure all systems are operational and send an initial health data packet to the ground station.

The AUV will then enter Phase 2, where it will start by diving to a target depth of up to 3.66m. Once at the target depth, the AUV will spin in place until it identifies a point of interest (POI) using an onboard visual-depth camera an instance segmentation neural network. At this stage, the AUV will slow down and center the POI in frame before approaching it. During the approach, the control system will use data from the camera to keep the POI in center frame and will slow down to stop once the POI encompasses 30% of the frame. The AUV will then take pictures of the POI and collect visual depth data before engaging in another spin to look for a new POI.

After 15 minutes of exploration, the AUV will enter Phase 3 where it will return near the surface, look for the drop point marker, and return to it if found. When the AUV has returned to the drop point or completed a spin without finding the drop point marker, it will resurface for a strictly-timed 5 minute communication window. The AUV will then use an onboard Wi-Fi transmitter to search for and connect to the ground station on the pool deck. Once connected, the AUV will downlink important telemetry data, a system health data packet, and images of all POI encountered. The AUV may also receive uplink commands from the ground station during this communications window. At the end of the communications window, the AUV will return to Phase 2 and repeat this process a total of 3 times for a 60 minute mission duration. At the end of the third cycle, the AUV will be commanded to power down its systems, and then it will be retrieved from the pool, ending the mission.

2.1. Levels of Success

Main Metrics					
Level	1	2	3	4	5
Object Detection	-Single-class (1 color) -Stationary -Simple object (uniform dimensions)	-Multi-class (more than 1 color) -Stationary -Simple object (uniform dimensions)	-Multi-class (more than 1 color) -Stationary -Complex object (non-uniform dimensions)	-Moving objects (non-stationary) -Multi-class (more than 1 color) -Complex object (non-uniform dimensions)	-
Navigation	-Rotates in place (without explicitly commanded translation)	-Rotates in place then moves towards POI	-Rotates in place -Moves towards POI -Repeat for mulitple POIs	-Rotates in place -Moves towards POI -Repeats for multiple POIs -For each POI, orbit keeping the area of the bounding box of the POI wtihin 30-40% of the total image area	-
Collision avoidance (needs Navigation level 2)	-	-Comes to a complete stop before hitting an object (POI, wall, or junk) in view of front RGB camera -Holds position	-Navigates around "junk" object in view -Detects "junk" object in view of front RGB camera and moves to the left or right until junk is out of frame -Moves forward past obstacle	-Can navigate around multiple "junk" objects in view -Detects "junk" objects in view of front RGB camera -Moves left or right until all obstacles are out of frame or if there's sufficient space between them, then move sideways until the AUV is between the obstacles -Proceeds to move forward past obstacle	-Avoids walls even when not in view -In addition to level 4 capabilities, AUV can avoid walls that are not view of the front RGB camera
Imaging	-Capture at least 1 image of POI, where POI is at least partly in the frame	-Capture at least 1 image of POI, where POI is fully in frame	-Capture multiple images of POI, where POI is fully in frame	-Capture image of POI from multiple angles	-
Downlink	-AUV health packet reported to ground station during communication period	-Images, temperature data, and pressure data reported to ground station	-	-	-
Uplink	-Can recieve kill-switch command from ground station during communication period	-Can be commanded to return to a specific search depth	-Can be commanded to look for a specific class of object	-	-
Surfacing	-Moves straight up to surface and can remain on surface	-Rotates once to look for drop point marker -If found, returns to within 2 m of drop point before surfacing -Otherwise, resurfaces in place	-Returns to drop area using IMU data while looking for drop point marker -If marker found, returns to within 2 m of drop point before surfacing -If marker not found within 2 minutes, surface in place	-Returns to within 2 m of drop point without a marker, then surfaces	-

Figure 3: Primary Levels of Success

The primary levels of success are those which directly pertain to the specific mission of the AUV. The ones highlighted in blue are the target levels for base functionality. The ones above those are targets for extra time if it is available. In particular, Object Detection is the primary category to receive extra time. If any of these fall below level 1, the AUV will still be functional by the strict definition of AUV, though the mission will be a failure as it does not accomplish any of its goals.

Auxillary Metrics					
Metric	Level				
	1	2	3	4	5
Preparation	AUV ready to go with less than 15 minutes preparation	Less than 10 min preparation	Less than 5 min preparation	No assembly required	No calibration required
Drop	Survives a 2.5 ft (up to 3) drop into water at one orientation	Survives a 2.5 ft (up to 3) drop with small rotational motion	Survives a 2.5 ft (up to 3) drop at any orientation	-	-
Waterproofing	Water-sensitive internal components are safe for the mission duration	No water leakage from the outside	No internal condensation	-	-
Dive	Stays underwater no deeper than 12 ft	Stays within 3 ft of target depth	Stays within 1 ft of target depth	Stays within 6 in of target depth	-
Kill Switch	Kill switch immediately cuts power to all components. Triggered by manual button on outside	Triggered by command from ground station	Triggered by positive signal from internal water sensor	Triggered by internal temperature coming within 5 degrees C of lowest component maximum	-
Depth Accuracy (needs Navigation level 2)	-	Determines distance to any object in range with ± 3 ft accuracy	Determines distance to any object in range with ± 1.5 ft accuracy	Determines distance to any object in range with ± 1 ft accuracy	-

Figure 4: Auxiliary Levels of Success

The auxiliary levels of success are those that pertain to the general operation of AUVs. The ones highlighted in yellow are the targets for base functionality. In addition, the higher levels here are less essential compared to the primary levels, so they are less likely to receive any additional time. If any of these fall below level 1, the AUV is not functional at all.

2.2. Functional Requirements

Table 1: Functional Requirements Matrix

ID	Assoc ID	Requirement	Rationale	Source
001	*1*	*Vehicle Requirements*		
002	**1.1**	**The vehicle shall be self-powered**	**External power sources are ineffective in an underwater environment.**	**Lockheed Martin - simulating need for AUV to operate on its own on Europa**
005	**1.2**	**The vehicle shall take no longer than 15 minutes to prepare**	**Vehicle can be easily assembled and disassembled with simple and minimal tools to decrease testing time**	**Lockheed Martin - typical requirement for AUV competitions**
006	**1.3**	**~~The vehicle shall complete its mission without external ambient light~~ The vehicle shall operate an onboard light(s)**	**The Europa environment has no ambient light - RESCOPE: unable to gain access to completely dark pool**	**Lockheed Martin - simulating lack of light on Europa**
007	**1.4**	**The vehicle shall not utilize pyrotechnic or chemical sources of illumination**	**Pyrotechnic and chemical illumination is temporary without a fuel for it**	**Lockheed Martin - ensure no harmful agents introduced to a pool**
009	**1.5**	**The vehicle shall complete mission objectives at depths up to 4 meters**	**Four meters is a common and readily available depth of for a test environment**	**Lockheed Martin - constrain our design to a reasonable depth**

ID	Assoc ID	Requirement	Rationale	Source
012	**1.6**	**The vehicle shall operate in water temperatures ranging from 0C to 35C**	**The ocean environment on Europa unknown, so the AUV must be able to operate in a wide range of temperatures**	**Lockheed Martin - constrain thermal testing of our project**
014	*2*	*Control Requirements*		
015	**2.1**	**The vehicle shall operate without manual control**	**Manual control will not be possible for a vehicle on Europa**	**Lockheed Martin - autonomy is primary concern for this project, want minimal human interaction**
022	*3*	*Telemetry Requirements*		
023	**3.1**	**The system shall report telemetry data defined below**	**The following telemetry categories are important for controlling the vehicle, making navigation decisions, and studying the environment**	**Lockheed Martin - this is the data the AUV would need to send from Europa to characterize the state of the environment and the AUV**
024	**3.1.1**	**Environmental Conditions**	~	~
027	**3.1.2**	**Power System Health**	~	~
028	~~**3.1.3**~~	~~**Relative Vehicle Location**~~	~	~
029	**3.1.4**	**Points of Interest**	~	~
030	**3.1.5**	**Images**	~	~
032	**3.2**	**The system shall downlink image data**	**An eventual mission to Europa would require a way to return data and images to Earth**	**Lockheed Martin - simulate transmitting visual data to understand the conditions on Europa**
034	**3.3**	**The telemetry shall be stored for post mission analysis**	**If any data is not properly downlinked, it can still be analyzed post mission and testing**	**Lockheed Martin - want to observe hwo our solutions parses through data**
036	*4*	*Communication Requirements*		
037	**4.1**	**The system shall downlink data in 20 minute intervals for durations of up to 5 minutes**	**The vehicle can only downlink while on the surface of the water, which is not the environment desired for study, so the time spent downlinking must be limited**	**Lockheed Martin - simulate access the team would have on a mission to Europa**
038	**4.2**	**The system shall uplink data in 20 minute intervals for durations of up to 5 minutes**	**The vehicle can only uplink while on the surface of the water, which is not the environment desired for study, so the time spent uplinking must be limited**	**Lockheed Martin - simulate Deep Space Network integration**
041	*5*	*Demonstration Requirements*		
042	**5.1**	**The vehicle shall navigate on closed course no larger than 50 x 25 x 3.65 meters**	**A test volume greater than this would be difficult to find in Boulder**	**Lockheed Martin - bound our course creation**

ID	Assoc ID	Requirement	Rationale	Source
046	**5.2**	**The vehicle shall mark points of interest**	**The ability to differentiate objects within the surroundings will make observing the data easier for the ground station operator**	**Lockheed Martin - due to communications blackout, Europa mission will have to autonomously identify interesting data**
048	**5.3**	**The vehicle shall withstand impact to surface of body of water from 0.77 m above surface**	**Conceptually on a Europa mission, the AUV may be dropped into the ocean from a lander**	**Lockheed Martin - common AUV competition rule**
050	**5.4**	**The vehicle shall be recoverable**	**AUV must be recoverable to be reused**	**Lockheed Martin - potential to test the vehicle again**
051	***6***	***Safety Requirements***		
052	**6.1**	**The vehicle shall prevent electrical discharge**	**Safety of all participants is the first priority**	**Lockheed Martin - ensure no harm comes to people during testing**
053	**6.2**	**The vehicle shall prevent circuit overloads**	**Circuit overloads could destroy the electronics system and other sensors**	**Lockheed Martin - ensure electronics are still usable post-delivery**
054	**6.3**	**The vehicle shall not leak environmentally hazardous materials**	**Safety of all participants is the first priority**	**Lockheed Martin - ensure no hazardous materials injure testing team or passersby**
055	**6.4**	**The vehicle shall pass a customer safety inspection**	**Safety of all participants is the first priority**	**Lockheed Martin - wants to sign off on safety of AUV prior to testing to ensure team is safe**
056	**6.5**	**The vehicle shall meet the MIL-STD-1472G for 5-95% male and female to 1 meter**	**The AUV needs to be easily transportable for safety**	**Lockheed Martin - AUV is safe for team members to carry and manipulate**
058	**6.6**	**The vehicle shall incorporate a kill switch**	**A kill switch ensures safety of the AUV and the team**	**Lockheed Martin - vehicle shuts down whenever it or a team member is threatened**
061	**6.7**	**The vehicle shall possess safety labels and markings**	**Safety of all participants is the first priority**	**Lockheed Martin - designate where the vehicle is hazardous to interact with**
062	**6.8**	**The vehicle shall be no larger than 2’ x 2’ x 2’**	**Ability to fit within standard payload volume**	**Lockheed Martin - simulate constraints of Europa launch**

3. Design Process and Outcome

Forrest Barnes, Benjamin Bruce, Colin Claytor, Griffith Kull, Christian Mitchell, Jacob Siegel, Caleb Sytner, Micah Zhang

3.1. Design Alternatives and Trade Studies

3.1.1. Software

Using the IMU for localization would entail using at least three accelerometers to measure the acceleration of the AUV. This can provide a measure of localization by integrating over the acceleration twice to find a relative position compared to where the AUV started. However, this does not provide much drift mitigation, as drift is a comparatively small, constant velocity. In addition, most accelerometers are not accurate, and those inaccuracies are made even greater after the integration. Returning to a specific location would be difficult relying on the IMU as a result. Also, there is no ability to react to environmental features using the IMU, limiting its use for navigation.

Table 2: Pros and Cons List for an IMU

Pros	Cons
Easy to implement	Inaccurate
Cheap	Little drift mitigation

Using the 360° camera for localization would entail using a 360° camera to watch for the boundaries of the test environment and points of interest. In addition, a second camera would be used to add depth perception to the view of the AUV to allow for distance measurements, allowing for localization relative to objects within sight. However, the view of the camera is distorted underwater, so the accuracy of this method is rather low.

Table 3: Pros and Cons List for a 360° Camera

Pros	Cons
Doubles as the science camera	No depth perception
Cheap	Extremely difficult to implement drift mitigation
Can help with object identification	Limited range

The landmark detection method of localization revolves around building a cylindrical coordinate system using a rangefinder and a magnetic compass. The rangefinder would have to keep track of a landmark at all times and record the distance to it. That relative position vector, in combination with the magnetic compass, allows for localizing the AUV within a cylindrical coordinate system with the landmark at the origin. Any points of interest encountered can have a position recorded with this frame to attempt to return later. However, the ability to track the landmark with the rangefinder either requires a circular navigation pattern around the landmark, or the ability to move the rangefinder relative to the AUV. This makes implementation of this method much harder. In addition, if the chosen landmark moves during the test, the entire frame is shifted, but shifting the recorded location data would be difficult using just the data provided by the rangefinder.

Table 4: Pros and Cons List for Landmark Detection

Pros	Cons
Accurate	Difficult to implement
Good drift mitigation	Mechanically complex (moving sensor)

The scanning imaging sonar is a 360° sonar that translates the environment around the AUV into a 2D plot with color coding for relative distance. The range on this device would cover the entire test environment, allowing for the construction of a Cartesian coordinate system using one corner of the environment as the origin. In addition, this would allow the object identification system to notice 3D objects, as well as inform the navigation system about obstacles. The sonar is also very accurate compared to using a camera. However, the scanning imaging sonar is a very expensive sensor, so damage to it would be a large problem. In addition, the sonar cannot see directly above or below the AUV, requiring some sort of rangefinder on the bottom to ensure the AUV does not collide with the floor of the test environment.

Table 5: Pros and Cons List for Scanning Imaging Sonar

Pros	Cons
Accurate	Difficult to implement
Good drift mitigation	Expensive
Helps with both navigation and object identification	

Sonar triangulation is a method that utilizes three sonar systems. The three sonars would measure distance relative to objects within the test environment, including the walls. Three are required because each sonar only can tell distance. Therefore, each sonar draws a circle with a radius of the measured distance on which the object can be. The intersection of the three circles from all of the sonar systems would allow an accurate idea of its surroundings. However, within the confined volume of the test environment, the secondary reflections of all of the sonar systems would interfere with each other, causing inaccuracies to pile on very rapidly. This is a method that would work well on an actual Europa mission, but loses almost all of its use within the confines of the test environment.

Table 6: Pros and Cons List for Sonar Triangulation

Pros	Cons
Good for Europa	Very little accuracy within pool
Good drift mitigation	Difficult to Implement
Helps with both navigation and object identification	

LIDAR triangulation works the same as sonar triangulation, but uses LIDAR instead. However, this is far more expensive. LIDAR would be more accurate, except that the LIDAR emission loses virually all of its energy only a couple of centimeters into the water, rendering it virtually useless in the underwater environment.

Table 7: Pros and Cons List for LIDAR Triangulation

Pros	Cons
Accurate	Expensive
Helps with object identification	Severely limited range

The DVL is a sensor that uses a single sonar to measure the distance to the bottom of the test environment, as well as the AUV's velocity relative to the floor. This makes this by far the best method of drift mitigation, as it can measure the exact velocity that the vehicle needs to counter. In addition, it can be used to measure position more accurately than the IMU due to being a more accurate sensor, as well as only needing to integrate once to obtain position. However, the DVL is more expensive than any of the other options except for LIDAR, with both of those options costing more than the entire budget of the project. In addition, the DVL cannot help with object identification at all.

Table 8: Pros and Cons List for DVL

Pros	Cons
Accurate	Expensive
Completely mitigates drift	No overlap with object identification

Table 9: Localization Trade Study Metrics

Trade Study I - Localization						
Metric	**0**	**1**	**2**	**3**	**4**	**5**
Usability in Pool	N/A	Loses all usefulness within the confined pool environment	Has very large errors within the confined pool environment	The confined pool environment introduces some noticable error	Works well within the confined pool environment with minimal error	Is ideal for the confined pool environment
Effectiveness for Drift Mitigation	N/A	Cannot mitigate drift at all	Is not effective for mitigating drift	Reduces the error introduced by drift	Greatly reduces the error of introduced by drift	Eliminates drift as a problem for localization
Ability to Return to Base	N/A	Provides no ability to return to a given location	Provides minimal information relevant to returning to a given position	Provides some information relevant to returning to a given position	Can return to within 2 m of a desired location	Can return to within 0.5 m of a desired location
Difficulty of implementation	Is an area of active research. Solving this should be a Master's Thesis.	Would take a significant amount of time to learn the requisite skills to implement	Would require extra learning, as well as take a larger amount of time to implement	Would require some extra research and/or learning to implement	Could be implemented with current skill set, but would take a larger time investment	Could be implemented easily with current skill set
Applicability to Europa	N/A	Would be virtually useless in the Europa environment	Would only be rarely useful within the Europa ocean	Would lose most of its utility/accuracy within the Europa ocean	Would lose some accuracy within the Europa ocean environment	Would transfer perfectly to the Europa ocean environment
Applicability to Object Identification	Provides no relevant data to object identification	Is virtually irrelevant to object identification	Can be used for object avoidance, but not detection/identification	Provides limited information about objects in the surrounding area	Is very useful for locating/identifying objects of interest	Can identify and photograph objects of interest
Applicability to Navigation	N/A	Is virtually irrelevant to navigation	Is useful for navigation only in very limited circumstances	Provides data relevant to navigation	Can be a primary component of the navigation system	Is totally sufficient for all navigation requirements
Cost	Has a cost greater than the available budget	Consumes over 50% of the budget	Consumes over 30% of the budget	Consumes over 20% of the budget	Consumes over 10% of the budget	Consumes under 10% of the budget

Table 10: Localization Trade Study Results

Trade I - Localization								
Metrics	**Weight**	**IMU**	**360 Camera**	**Landmark Detection**	**Scanning Imaging Sonar**	**SONAR Triangulation**	**LIDAR Triangulation**	**DVL**
Usability in Pool	15%	5	3	3	5	2	1	5
Effectiveness for Drift Mitigation	15%	3	2	4	3	3	2	5
Ability to Return to Base	10%	1	3	5	5	4	2	3
Difficulty of implementation	10%	5	1	1	3	1	1	5
Applicability to Europa	5%	5	4	2	4	4	1	5
Applicability to Object Identification	10%	0	5	0	4	3	4	0
Applicability to Navigation	10%	2	3	4	5	3	2	2
Cost	25%	5	5	4	3	4	0	0
TOTAL	**100%**	**3.5**	**3.4**	**3.15**	**3.85**	**3.05**	**1.4**	**2.75**

The results of the trade study pointed towards the scanning imaging sonar. However, this proved too expensive to justify afterwards, and so a variant on the 360 Camera was considered. Rather than use a true 360 camera, the Intel RealSense T265 and D435 could be used together to provide localization. The package also came with its own VSLAM algorithm built in. It was demonstrated to work in air, however it was discovered that the lack of features in the pool other than POI, in addition to the inaccuracy of the built in IMUs, would render the localization data inaccurate. After a discussion with the customer team, localization was eventually descoped as a requirement.

Table 11: Navigation Trade Study Metrics

Trade Study II - Navigation					
Metric	**1**	**2**	**3**	**4**	**5**
Difficulty of Implementation	Would take a significant amount of time to learn the requisite skills to implement	Would require extra learning, as well as take a larger amount of time to implement	Would require some extra research and/or learning to implement	Could be implemented with current skill set, but would take a larger time investment	Could be implemented easily with current skill set
Relevance/ Usefulness for Europa	Would be virtually pointless to consider for an actual Europa mission	Might have a rare application for an actual Europa mission	Might be useful as a backup/extra system for an actual Europa mission	Could be feasible for an actual Europa mission	Would be useful on an actual Europa mission
Time to Execute for 1 POI	Takes up to 20 minutes to execute for finding max number of POI, possibly too slow for exploration window	Will take up most of the exploration window	Will take up a significant portion of the exploration window	Takes little additional time beyond the direct travel time	Only takes the time needed to travel the direct route. 'As the crow flies'
Usability in Pool	Essentially useless in use the scope of objectives in the pool	Only able to carry out some pool objectives, and in a limited capacity	Able to either carry out most pool objectives with limited capacity, or some objectives with no constraints	Able to carry out all pool objectives with some constraints	Able to navigate pool and carry out all mission objectives with no constraints, and a high degree of accuracy
Mechanical Complexity	Requires 6 DOF	Requires 4-5 DOF with lateral translation	Requires 4-5 DOF	4 DOF	Requires only forward, yaw, and vertical control. 3 DOF

Table 12: Navigation Trade Study Results

Trade Study II - Navigation				
Metrics	**Weight**	**360 degree search. Straight-line motion with collision avoidance to target. Circular movement around object of interest**	**Gradient search with collision avoidance for POI. Circular manuevers around POI while taking data and mapping surroundings**	**Lawnmower style search pattern based on FOV w/ collision avoidance while marking POI. POI coordinates passed to path planner, followed up by direct inspection.**
Difficulty of Implementation	15%	3	4	5
Relevance/Usefulness for Europa	10%	4	2	2
Time to Execute for One POI	20%	4	3	1
Usefulness in Pool	40%	5	3	4
Mechanical Complexity	15%	2	3	5
TOTAL	**100%**	**3.95**	**3.05**	**3.5**

Table 13: Object Identification Trade Study Metrics

Trade Study III - Object Identification					
Metric	1	2	3	4	5
Minimum # of Sensors Required	Several sensors are necessary	Requires 4-5 sensors	Requires 3 sensors	Requires 2 sensors	Only one sensor required
Ease of Identification	Cannot accurately identify or consistently notice a point of interest	Can notice points of interest, but cannot identify them	A point of interst must be visible for a time to be both noticed and identified	Can quickly notice points of interest, but requires time to identify them	Can easily and quickly notice and identify points of interest
Ease of Implementation	Would take a significant amount of time to learn the requisite skills to implement	Would require extra learning, as well as take a larger amount of time to implement	Would require some extra research and/or learning to implement	Could be implemented with current skill set, but would take a larger time investment	Could be implemented easily with current skill set
Relevance/Usefulness for Europa	Would be virtually pointless to consider for an actual Europa mission	Might have a rare application for an actual Europa mission	Might be useful as a backup/extra system for an actual Europa mission	Could be feasible for an actual Europa mission	Would be useful on an actual Europa mission

Table 14: Object Identification Trade Study Results

Trade III - Object Identification				
Metrics	**Weight**	**QR Code Scanning**	**2D Object Detection via Neural Networks**	**3D Object Detection via 360 Sonar and Neural Networks**
Minimum # of Sensors Required	15%	5	5	4
Ease of Identification	20%	5	4	4
Ease of Implementation	25%	5	3	3
Relevance/Usefulness for Europa	40%	1	3	5
TOTAL	**100%**	**3.4**	**3.5**	**4.15**

3.1.2. Electronics and Hardware

The power supply is a key element in the design of a AUV. Based on the current mission requirements, the power supply design has a large effect on the success of the mission as the AUV must operate for a specified period of time, meet a weight and size requirement, and complete mission objectives. A trade study was conducted to determine a battery chemistry that will best allow the AUV to meet the mission requirements and can be seen in Tables 15 and 16 below. Eight battery chemistries were studied and evaluated based on metrics described in Table 15 to assist in choosing the best design. The battery chemistries researched for this study were: Lead-Acid, Lithium-Ion, Lithium Polymer, Nickel-Cadmium, Nickel-Zinc, Nickel-Metal Hydride, Lithium Thionyl Chloride (LiSOC12), and Zinc Air.

The metrics chosen to evaluate these battery types and the scoring of each metric can be found in Table 15. The energy density of the battery type was the most important metric in deciding a battery type since the AUV must complete a mission of a specified time duration while staying within weight and size requirements. The next most important metrics are the battery type's maintenance complexity, cycle life, and cost. The maintenance complexity and peak load current are important metrics to consider since the battery will be required for testing frequently and must be able to power all components of the AUV while factoring in the safety of the team. The maintenance complexity metric encompasses many undesirable battery characteristics such as long charge time, careful charging requirements, memory effects, high self discharge rate, long assembly time, and whether the chemistry is an emerging technology. Careful recharging means that the process of charging the battery must be controlled precisely or the performance of the battery may degrade. The cost of the battery is an important metric since the project has a limited budget. The general cost of the battery types was calculated by choosing an arbitrary but reasonable battery capacity of 20 Ah and minimum voltage of 12 V, and finding the cost of each battery type that met these values.

Table 15: Battery Chemistry Trade Study Metrics

Trade V - Power Supply					
Metric	**1**	**2**	**3**	**4**	**5**
Energy Density (Wh/kg)	<30	30 - 60	61 - 100	101 - 179	>180
Peak Load Current (C)	<1	1 - 2	3 - 5	6 - 10	>11
Cycle Life	1 (non-rechargeable)	<100	100 - 300	300 - 500	>500
Maintenance Complexity	4 of the following: Long charge time, requires careful charging, memory effects, high self discharge rate, emerging technology, long assembly time	3 of the following: Long charge time, requires careful charging, memory effects, high self discharge rate, emerging technology, long assembly time	2 of the following: Long charge time, requires careful charging, memory effects, high self discharge rate, emerging technology, long assembly time	1 of the following: Long charge time, requires careful charging, memory effects, high self discharge rate, emerging technology, long assembly time	No complex maintenance
Cost	>$400	$301 - $400	$201 - $300	$100 - $200	<$100

Table 16: Battery Chemistry Trade Study Results

Trade V - Power Supply									
Metrics	**Weight**	**Lead Acid**	**Lithium-ion**	**LiPO**	**NiCad**	**NiZn**	**NiMH**	**LiSOCl2**	**Zinc Air**
Energy Density	30%	1	5	5	2	5	3	4	4
Peak Load Current	20%	3	3	3	5	2	3	1	1
Cycle Life	10%	3	5	4	5	3	4	1	1
Maintenance Complexity	20%	3	4	3	1	3	3	3	2
Cost	20%	5	2	1	1	4	4	1	1
TOTAL	**100%**	**2.8**	**3.8**	**3.3**	**2.5**	**3.6**	**3.3**	**2.3**	**2.1**

The results of this trade study led to choosing a baseline power supply design of lithium based battery chemistry. Lithium based batteries scored the highest in the trade studies since they have a high energy density and require low maintenance. It is beneficial to have a high energy density to allow the battery to power the AUV for the entire mission duration while minimizing the volume required for the battery within the AUV's enclosure. A low maintenance battery also eases in the testing processes as the battery will be used heavily while testing and manufacturing the AUV. Since further designing the AUV and gaining an understanding of the power required for the mission, a Lithium Iron Phosphate battery has been chosen as it meets the power and volume requirements at a low cost.

3.1.3. Mechanical

Five general AUV designs were chosen to study. The first being a traditional torpedo with control fins. Second is also a torpedo, but it uses motors to provide control movements. Third is a Non-Torpedo with 4-5 DOF and the fourth is also a Non-Torpedo, but with all 6 DOF. Last is a Non-Torpedo with gimbaling motors to provide the 6 DOF. The next few sections will go over the five designs in more depth and provide a pros and cons list for each.

Traditional Torpedo with Control Fins

This design is based on a traditional AUV design; the body of the AUV is a long, slender tube with one motor at the back and fins to control pitch and yaw. A general design is given in Fig. **??**.

The electronics will be housed in the tube of the AUV, and the front hemispherical end cap will be transparent to allow a camera to scan the environment. Pressure and temperature sensors will be placed along the hull. The AUV will control its depth with an air ballast system. The pros and cons of this design are summarized in Table 17.

Table 17: Pros and Cons List for the Traditional Torpedo Design

Pros	Cons
Simple to design and manufacture	Low maneuverability
Low drag	Cannot counter lateral drift
Lower cost	Complex ballast system
Easy to water-seal	
Stronger against impacts	

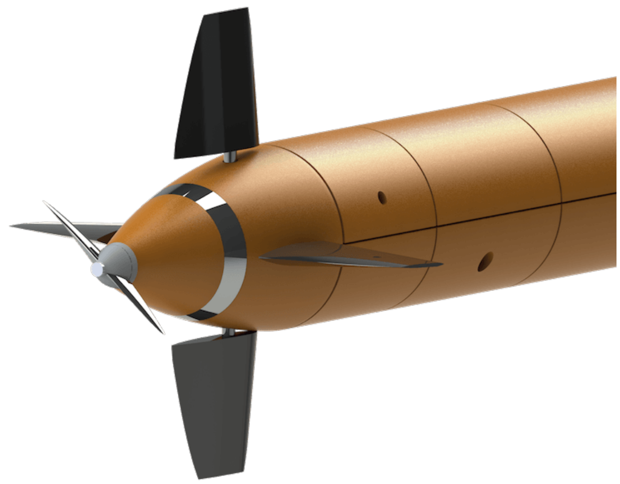

Figure 5: Example of Traditional Torpedo Design with Control Fins,[12]

Torpedo with Control Motors

This design is similar to the traditional torpedo design outlined above, with the exception that it uses motors for yaw and pitch control. This would eliminate the need for moving fins and would grant the AUV additional degrees of freedom depending on how these additional motors are placed, eliminating the need for a complicated ballast system. Once again, the front end cap will be transparent to allow a camera to scan for items of interest, and pressure and temperature sensors would be placed along the hull. A pros and cons list for this design is given in Table 18 and a general diagram of this design is shown in Fig. 6.

Table 18: Pros and Cons List for the Torpedo Design with Control Motors

Pros	Cons
Simple to design and manufacture	Low maneuverability
Low drag	Cannot counter lateral drift
Lower cost	More motors adds cost
Easy to water-seal	Higher power draw
Stronger against impacts	

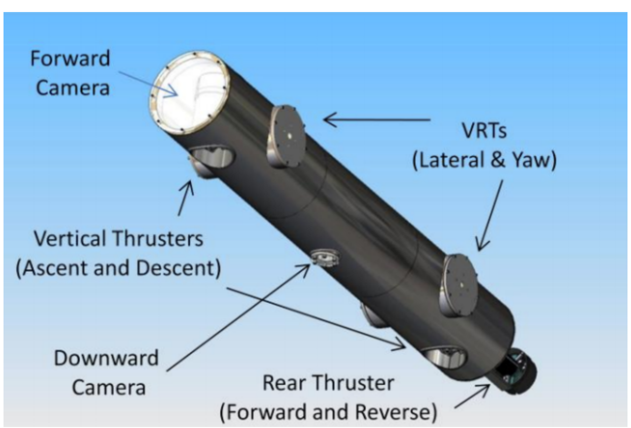

Figure 6: Example of the Torpedo Design with Control Motors,[7]

Non-Torpedo (4-5 DOF)

This design moves away from the basic torpedo design and takes a form closer to the design of an ROV. Like the above designs, the electronics and camera would be sealed in a tube, but the tube will be supported in a frame that holds motors pointing in the desired directions. There would be 4-6 motors on the AUV, giving it 4-5 degrees of freedom. The placement of the motors would be based on which DOF were determined to be most important and which could be omitted. A diagram and a list of pros and cons for this design can be found below in Fig. 7 and Table 19, respectively.

Table 19: Pros and Cons List for the Non-Torpedo Design with 4-5 DOF

Pros	Cons
Decent maneuverability	Requires more structure
Can counter most drift	High drag
Easier programming architecture	More motors adds cost

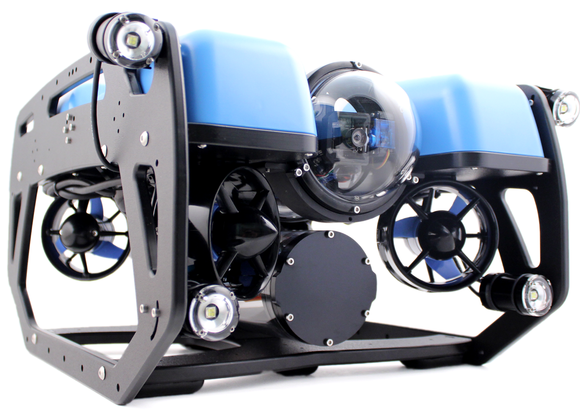

Figure 7: Example of Non-Torpedo AUV with 4-5 DOF,[4]

Non-Torpedo (6 DOF)

This vehicle design incorporates the same general shape as the previous Non-Torpedo (4-5 DOF) design as a ”boxier” shape. Again, the electronics will be inside a watertight tube. This tube will be supported by a chassis that will hold the motors in the desired positions. However, unlike the previous option, this will incorporate 8 motors in order to achieve all 6 degrees of freedom while retaining full redundancy. Thus giving this design the best maneuverability. A diagram and a list of pros and cons for this design can be found below in Fig. **??** and Table 20, respectively.

Table 20: Pros and Cons List for the Non-Torpedo Design with 6 DOF

Pros	Cons
Highest maneuverability	Requires a lot of structure
Can counter any drift	High drag
Easiest software control architecture	More motors adds cost

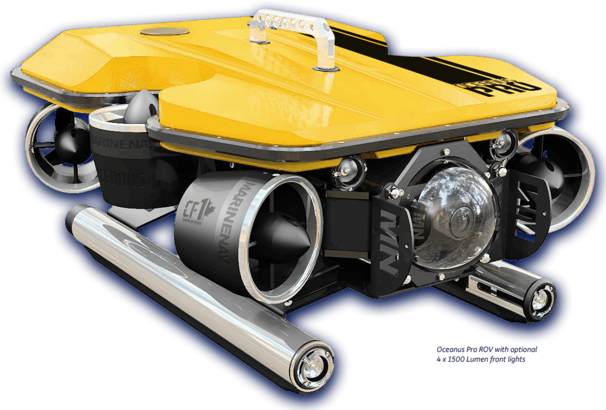

Figure 8: Example of Non-Torpedo AUV with 6 DOF,[16]

Gimbaling Motors (4-5 DOF)

This design also allows for the vehicle to utilize all 6 degrees of freedom. However, unlike the previous design this design would use fewer motors. This is accomplished by utilizing servos to gimbal or articulate the motors. Like the designs above, the electronics would be sealed in a watertight tube that is supported by a chassis that holds the motors and servos. A diagram and a list of pros and cons for this design can be found below in Fig. 9 and Table 21, respectively.

Table 21: Pros and Cons List for the Gimbaling Motor Design

Pros	Cons
High maneuverability	Requires the most structure
Can counter any drift	Response may lag
Less Motors	Requires servos
	Highest mechanical complexity
	More difficult programming architecture

Figure 9: Example of Non-Torpedo AUV with Gimbaling Motors[22]

The next couple of sections talk about the metrics and scoring associated with each design. Table 22 shows the criteria that each design was scored off of along with the five studied designs along the top row of Table 23 and their scores along the bottom.

Diving into the actual metrics of Table 22, maneuverability is based on the number of DOF the AUV would have. At minimum, the AUV was required to have forward, yaw, and vertical control. More DOF would also decrease the navigation complexity as it is easier for the software team to program the navigation system. A larger suite of sensors would also be important to decrease the navigation complexity, but is covered in a different trade study and will not be taken into account here. Drift mitigation is based on the AUV's ability to counter any external forces and moments, whether it be by water currents or jets. Note that this metric has been de-scoped for the final design due to the localization de-scoping. In essence, it was found not important and out of the project's scope to try and map out the location of the AUV. It will now simply roam around until it finds a POI. Drag is the next metric and is based on the hyrdrodynamics of the body. For example, a sleeker torpedo would have a better score for drag, but this also at a cost as it decreases the maneuverability. Cost is primarily based on the number of motors that the design requires. The cost of materials is negligible compared to the cost of the motors. Manufacturability is scored based on the difficulty for the mechanical team to build the AUV within the given time constraints. Water seal complexity is solely due to the amount of wires that would be penetrating the hull. This increases the risk for water intrusion, so the lesser amount of wire penetrations is desired. One of the main driving factors for this is the amount of motors, as each motor will require a wire penetration.

Table 22: Vehicle Shape Trade Study Metrics

Trade IV - Vehicle Shape/Layout					
Metric	**1**	**2**	**3**	**4**	**5**
Maneuverability	Only has forward, yaw, and vertical control. 3 DOF	4 DOF	4-5 DOF	4-5 DOF. Can translate laterally	6 DOF
Navigation Complexity	Most difficult method for software to program	Difficult for software to program due to limited DOF	Moderately difficult for software to program, but achievable	Easy method for software to program, but one more DOF would be desired	Easiest method for software to program the vehicle to move appropiatly (requires all 6 DOF)
Drift Mitigation	No ability to react to an external lateral force, roll moment, or pitch moment	Has ability to react most external forces and most moments	Has ability to react to any external force and most moments	Has ability to react due to most external forces and any moments	Has ability to react to all external forces and any moments
Drag	Rectangular box ~ CD = 2	Generally "box" shaped, but slightly optimized	Minimalistic box, with stream-lined components	Slight obstructions or protrustion from a long stream-lined body	Long streamlined body ~ CD = 0.1
Cost	8 motors/servos	6 motors/servos	5 motor/servos	4 motors/servos	3 motors/servos
Manufacturability	Highly unlikely to manufacture on time	Difficult to manufacture on time	Moderately difficult to manufacture on time	Achievable to manufacture on time	Manufacturing completion guaranteed
Water Seal Complexity	8 wire penetrations	6 wire penetrations	5 wire penetration	4 wire penetrations	3 wire penetraions

Table 23: Vehicle Shape Trade Study Metrics

Trade IV - Vehicle Shape/Layout						
Metrics	**Weight**	**Traditional Torpedo with Control Fins**	**Torpedo (Motor Propulsion for Yaw & Pitch)**	**Non-Torpedo (4-5 DOF)**	**Non-Torpedo (6 DOF)**	**Gimbaling Motors (6 DOF)**
Maneuverability	25%	1	3	4	5	5
Navigation Complexity	15%	1	3	3	5	3
Drift Mitigation	15%	1	2	3	5	4
Drag	5%	5	3	2	2	3
Cost	15%	5	4	3	1	1
Manufacturability	15%	5	3	3	2	2
Water Sealing Complexity	10%	5	4	2	1	1
TOTAL	**100%**	**2.8**	**3.1**	**3.1**	**3.4**	**3**

Traditional Torpedo with Control Fins

Maneuverability, 1: Due to control fins being the only surface acting to change directions, a traditional torpedo yields a limited number of DOF.

Navigation Complexity, 1: A limited number of DOF makes it difficult for the software team to program an accurate navigation algorithm.

Drift Mitigation, 1: The AUV has no ability to react to a lateral force due to limited controls.

Drag, 5: A traditional torpedo would be an ideal design to mitigate drag as it is streamlined and there are no protrusions along the body.

Cost, 5: There will only be 1 motor mounted to the rear of the AUV to act as a pushing force. One motor will only account for 3% of the budget.

Manufacturability, 5: This design is simply a straight tube, where the electronics sit on a track inside for ease of repairs. The main tube is easy to purchase or manufacture; however, manufacturing it may lead to the risk of an imperfect seal along the length of the shell which would compromise the structural strength. End caps are also easy to manufacture and O-rings will provide a adequate solution to waterproofing.

Water Sealing Complexity, 5: As the control fins and propeller are all located at the rear of the AUV, there is only a need to breach the compartment once in the rear. There will only be a maximum of 2 other breaches for the sonar system and the exterior lights.

Torpedo with Control Motors

Maneuverability, 3: Compared to the traditional torpedo, adding extra motor propulsion for yaw and pitch increases the maneuverability of the AUV as there are additional DOF. It still will have little control to counter a lateral force.

Navigation Complexity, 3: Added DOF will make it easier for the software team to create an accurate algorithm, but limited outboard sensors and maneuverability adds to the difficulty.

Drift Mitigation, 2: As mentioned, there are more DOF and allows the AUV to counter drift mitigation better than the traditional torpedo; however, there are still not enough DOF to mitigate drift in every direction.

Drag, 3: The overall shape of this is still a streamlined tube, but the additional side mounted motors will create extra drag.

Cost, 4: There will be at least 2 additional motors added to this design from the traditional torpedo found above. These will increase the overall cost as more motors must be purchased. 4 motors will most likely account for 12% of the budget.

Manufacturability, 3: This design is still fairly simple overall. The electronics will be housed inside of a long tube, but the compartment will need to be breached more than once to add the additional motors.

Water Sealing Complexity, 4: The extra motors mounted on the exterior of the tube will mean the compartment must be breached more than the traditional torpedo.

Non-Torpedo (4-5 DOF)

Maneuverability, 4: This design features at least 4 angled motors to control 4-5 DOF, placed symmetrically about the CG. Added DOF make this design more maneuverable than a torpedo.

Navigation Complexity, 3: The software team will still have a moderately difficult time designing an accurate navigation algorithm due to the fact that it does not have all 6 DOF.

Drift Mitigation, 3: The motor configuration allows a strong counter to any lateral forces, but moments may still be an issue.

Drag, 2: A box is not hydrodynamic and would create a large amount of drag when comparing to a streamlined torpedo. It will be slightly optimized to allow water to flow around most protrusions.

Cost, 3: More DOF require more motors and therefore will increase the cost of the AUV. 5 motors will likely account for 15% of the budget.

Manufacturability, 3: A box is more complex than a straight tube since there is more exterior structure in the water that may fail under different conditions. This would mean a more complex structure making it moderately difficult to create on time.

Water Sealing Complexity, 2: As mentioned, there are more exterior surfaces exposed to the water. Sensors, cameras, additional motors, and lights may all be placed outside of the main electronics housing which would require multiple wire breaches.

Non-Torpedo (6 DOF)

Maneuverability, 5: Additional motors mounted for vertical motion would allow the AUV full control over all 6 DOF.

Navigation Complexity, 5: The additional motors would allow the software to utilize all 6 DOF to build a navigation system. This would be the easiest to implement for them.

Drift Mitigation, 5: The ability to utilize all 6 DOF means that the AUV would be able to counter any external force or moment. This allows for a more accurate positioning system since drift could be considered negligible.

Drag, 2: Similar to the previous non-torpedo, the drag would mostly be caused by exterior surfaces protruding from the central housing. Components would be made as hydrodynamic as possible, but there will still a larger drag force when compared to the traditional torpedo.

Cost, 1: This design would require 8 motors in order to achieve a perfect 6 DOF design. Increased number of motors would be costly. 8 motors will likely account for 24% of the budget.

Manufacturability, 2: Increasing the number of motors means more structures must be attached to the central housing. This would take more time to build and may be cutting it close to deadlines.

Water Sealing Complexity, 1: 8 motors would mean that more wires must penetrate into the compartment. In addition to the motors, there are also lights, sonar, cameras, and other sensors that would create more breaches into the compartment.

Gimbaling Motors (6 DOF)

Maneuverability, 5: Gimbaling motors will allow 6 DOF with less outboard motors by the use of thrust vectoring.

Navigation Complexity, 3: The main difficulty with gimbaling motors is that the software team will have to program motors to rotate just the right amount in order to achieve an extremely accurate navigation algorithm. This would increase the complexity of the overall system.

Drift Mitigation, 4: 6 DOF make this design score high, but the the fact that rotating motors are in the equation make it more difficult to counter drift with precise thrust forces.

Drag, 3: The drag is better on this design since there are less outboard motors and therefore less protrusions.

Cost, 1: This would be still be expensive due the fact that 4 servos would need to be utilized to rotate the outboard motors. 8 motors/servos will likely account for 24% of the budget.

Manufacturability, 2: Gimbaling mechanisms are not easy to manufacture and would create additional breaches to the compartment for the thrust vectoring servos.

Water Sealing Complexity, 1: The additional breaches from servos make this design score very low.

The results of this trade study originally showed that the Non-Torpedo 6 DOF design is the best option. It was then concluded that a total of 8 motors would be used for the AUV to provide the 6 DOF. However, as costs began to rise for sensors needed for software, other sub-teams had to make cuts and it was decided that the high cost to purchase 8 motors would need to be brought down. This meant decreasing the motor count from 8 to 6, resulting in the final choice of a Non-Torpedo with 5 DOF. Originally, there were 4 vertical motors to provide pitch, roll, and sway. Decreasing to 2 vertical motors removed pitch as a DOF and was confirmed by the software team that it would not be a large setback. Pitch stability is also modeled and confirmed in section **??**.

3.2. Design Requirements

The functional and design requirements are tabulated below. Requirement sections appear in bold and are italicised, functional requirements simply appear in bold, and the design requirements appear in plain text.

3.2.1. Vehicle Requirements

Table 24: Requirement 1.1 Flow-down Matrix

ID	Assoc ID	Requirement	Motivation	Verification & Validation
001	***1***	***Vehicle Requirements***		
002	**1.1**	**The vehicle shall be self-powered**	**External power sources are ineffective in an underwater environment.**	**Vehicle operates under its own power for duration of test**
003	1.1.1	The vehicle shall store all electrical energy required to complete the mission in onboard batteries	Loss of power would result in loss of control of AUV	Vehicle operates under its own power for duration of test
004	1.1.2	The vehicle shall provide properly regulated voltage and current to electrical devices	Spikes in voltage and current can damage the AUV	The AUV completes mission undamaged

Functional requirement 1.1 details that the vehicle should be self powered, and two design requirements flow down from it: that the AUV shall use batteries and that the power throughout the AUV will be regulated by onboard systems. Very early in the development of the system it became clear that the only feasible way to propel the vehicle is through the use of electrically riven thrusters, and that a suite of onboard batteries would be necessary to drive these thrusters: this informed Req. 1.1.1. Because different systems on this AUV have different power requirements, Req. 1.1.2 was developed in order to ensure the team carefully develops and tests the electrical system of the AUV so that our electronics remain intact.

Table 25: Requirements 1.1-1.4 Flow-down Matrix

ID	Assoc ID	Requirement	Motivation	Verification & Validation
005	**1.2**	**The vehicle shall take no longer than 15 minutes to prepare**	**Vehicle can be easily assembled and disassembled with simple and minimal tools to decrease testing time**	**Assembly must be completed before a 15 minute timer expires.**
006	**1.3**	**~~The vehicle shall complete its mission without external ambient light~~ The vehicle shall operate an onboard light(s)**	**The Europa environment has no ambient light - RESCOPE: unable to gain access to completely dark pool**	**Incorporate light system into AUV**
007	**1.4**	**The vehicle shall not utilize pyrotechnic or chemical sources of illumination**	**Pyrotechnic and chemical illumination is temporary without a fuel for it**	**The vehicle does not have a pyrotechnic or chemical illumination system**
008	1.4.1	The vehicle shall be purely electrically driven	Electric power is the simplest way to have a sustainable power source	The AUV has an electric power source that can power the vehicle for at least one hour.

Functional requirement 1.4 reflects that no pyrotechnic or chemical illumination source was to be used on this AUV: this flows into design requirement 1.4.1, which prohibits the use of any equipment on the AUV that is not electrically powered. This prohibition of any non-electronic hardware ensures that not only this requirement is met, but the environmental contamination requirement as well.

Table 26: Requirement 1.5 Flow-down Matrix

ID	Assoc ID	Requirement	Motivation	Verification & Validation
009	**1.5**	**The vehicle shall complete mission objectives at depths up to 4 meters**	**Four meters is a common and readily available depth of for a test environment**	**The AUV can survive for one hour at 4 meters depth**
010	1.5.1	The vehicle shall withstand the water pressure at its mission depth	If the vehicle cannot withstand the water pressure, the electronics will be compromised	The vehicle can survive with no leakage for over one hour at the maximum depth
011	1.5.2	The vehicle shall maintain control of its depth	Without depth control, navigation in a 3D space is virtually impossible	The vehicle can be commanded to dive to a certain depth, which is then confirmed with a tape measure

Functional requirement 1.5 informs the maximum mission depth for the AUV, and is flowed down into design requirement 1.5.1 regarding withstanding pressure at depth, and design requirement 1.5.2 concerning depth control. 1.5.1 came from our decision to house all of our electronics in the a dry volume of air, and that this volume must be designed to withstand the pressure this AUV will endure. 1.5.2 was developed to describe that the AUV would decide what depth it would descend to and control itself during descent operations, as the team noted that the entirety of descent operations would need to be controlled by the AUV.

Table 27: Requirement 1.6 Flow-down Matrix

ID	Assoc ID	Requirement	Motivation	Verification & Validation
012	**1.6**	**The vehicle shall operate in water temperatures ranging from 0C to 35C**	**The ocean environment on Europa unknown, so the AUV must be able to operate in a wide range of temperatures**	**The AUV can survive for one hour in an ice bath as well as a bath as close to 35 degrees C as possible**
013	1.6.1	The vehicle shall be thermally tested in an aquatic environment	Without testing the vehicle in the target environment, there is no way to know how it will work while on mission	The vehicle is tested both in a temperature controlled tub and the test pool

Functional requirement 1.6 bounds the operating temperatures of the AUV, which flows into design requirement 1.6.1, the thermal test requirement. As the thermal model progressed, it became clear that the internal temperature of the AUV and managing the flow of heat would be of great consequence to us, meaning that the team will be testing to ensure the heat management mitigations function as intended.

3.2.2. Control Requirements

Table 28: Requirement 2.1 Flow-down Matrix

ID	Assoc ID	Requirement	Motivation	Verification & Validation
014	***2***	***Control Requirements***		
015	**2.1**	**The vehicle shall operate without manual control**	**Manual control will not be possible for a vehicle on Europa**	**The vehicle successfully executes its mission without human input**
016	2.1.1	The vehicle shall autonomously navigate underwater	The mission takes place underwater, so the vehicle must be able to move within the test course	The control system can move the vehicle within the underwater environment
017	~~2.1.1.1~~	~~The vehicle shall localize itself within its surroundings~~	DESCOPED: solutions for tracking vehicle location too costly for implementation here	~
018	2.1.1.2	The vehicle shall decide where to navigate	The ability to move is not useful without having a destination	The vehicle successfully moves towards POI and returns to dive point
019	~~2.1.1.3~~	~~The vehicle shall autonomously correct for drift and other errors~~	DESCOPED: solutions for tracking vehicle location too costly for implementation here	~
020	2.1.1.4	The vehicle shall recognize and avoid potential collisions immediately in front of it	Collisions have the potential to harm the AUV	The AUV successfully navigates around the POI tethers
021	2.1.2	The vehicle shall perform computations onboard	Due to being underwater, communications to an external computer would be impossible during the mission	The AUV's computers will successfully run the autonomy algorithm

Functional requirement 2.1 introduces the autonomy of the project, and 4 design requirements flow down from it. 6 design requirements used to flow down from it, but requirements 2.1.1.1 and 2.1.1.3 were dropped due to our discovery that the localization capabilities informally requested by Lockheed Martin were unreasonable. Design requirement 2.1.1 mandates that the AUV controls itself, which is integral to our mission success. Design requirement 2.1.1.2 introduces that the AUV must autonomously set a course and execute it, which is necessary if it is to survey points of interest that it spots. The next design requirement to flow down from 2.1 is 2.1.1.4, our collision avoidance requirement. The AUV impacting anything solid could crack its hull and destroy the sensitive electronics within, meaning it is integral for the AUV to recognize and avoid collisions. Design requirement 2.1.2 indicates that all autonomous operations will take place onboard the AUV, since running data cables behind the AUV would add undue complexity to the system and restrict its movement.

3.2.3. Telemetry Requirements

Table 29: Requirement 3.1 Flow-down Matrix

ID	Assoc ID	Requirement	Motivation	Verification & Validation
022	***3***	***Telemetry Requirements***		

ID	Assoc ID	Requirement	Motivation	Verification & Validation
023	**3.1**	**The system shall report telemetry data defined below**	**The following telemetry categories are important for controlling the vehicle, making navigation decisions, and studying the environment**	**The vehicle successfully stores and downlinks the following categories of telemetry**
024	**3.1.1**	**Environmental Conditions**	~	~
025	3.1.1.1	The vehicle shall record the external water temperature to telemetry at all times	~	~
026	3.1.1.2	The vehicle shall record its depth to telemetry at all times	~	~
027	**3.1.2**	**Power System Health**	~	~
028	~~**3.1.3**~~	~~**Relative Vehicle Location**~~	~	~
029	**3.1.4**	**Points of Interest**	~	~
030	**3.1.5**	**Images**	~	~
031	3.1.5.1	Image shall be distorted no more than 40% of above-water appearance	Too much image distortion makes study of the environment difficult	The distortion of an image compared to the same image above water shall be less than 40%

Functional requirement 3.1.1 details that the AUV must report on the environmental conditions it encounters. This flows into design requirement 3.1.1.1, which specifies water temperature should be reported, and design requirement 3.1.1.2 which describes that the vehicle should report its depth. These requirements exist to specify what the term “environmental conditions” means, and were agreed upon by Lockheed Martin as effective measures of the environment. Functional requirement 3.1.5 flows down into design requirement 3.1.5.1, which describes the allowable image distortion allowable for the AUV. If the AUV moves too quickly, the images produced by the camera on it may not be identifiable by our algorithm. By bounding the distortion, the team can ensure that the AUV has no difficulty identifying and observing points of interest in the pool.

Table 30: Requirement 3.2 Flow-down Matrix

ID	Assoc ID	Requirement	Motivation	Verification & Validation
032	**3.2**	**The system shall downlink image data**	**An eventual mission to Europa would require a way to return data and images to Earth**	**The vehicle can downlink its images during the downlink period**
033	3.2.1	The image data shall be downlinked within data packets containing other telemetry data	The temperature and pressure data are also important for both science and vehicle health purposes	The ground station receives images as well as pressure and temperature data

Functional requirement 3.2 describes how the AUV must downlink image data, and design requirement 3.2.1 clarifies that the images will be included in packets of data with other telemetry information. This requirement ensures that the uplink/downlink communication windows are efficiently utilized.

Table 31: Requirement 3.3 Flow-down Matrix

ID	Assoc ID	Requirement	Motivation	Verification & Validation
034	**3.3**	**The telemetry shall be stored for post mission analysis**	**If any data is not properly downlinked, it can still be analyzed post mission and testing**	**All of the data collected is also stored on the vehicle after a full mission**
035	3.3.1	The vehicle shall have enough storage to keep a profile of data from an entire "mission"	The mission requires sufficient storage size to hold all of the collected data	The AUV does not overwrite any files as it takes telemetry, nor does it drop telemetry

Functional requirement 3.3 demands that the telemetry data taken throughout the mission be stored for post-mission analysis. In order to meet this requirement without relying on the 5 minute uplink/downlink windows, design requirement 3.3.1 states that the AUV shall be capable of storing the telemetry data from one full mission onboard.

3.2.4. Communication Requirements

Table 32: Requirements 4.1-4.2 Flow-down Matrix

ID	Assoc ID	Requirement	Motivation	Verification & Validation
036	***4***	***Communication Requirements***		
037	**4.1**	**The system shall downlink data in 20 minute intervals for durations of up to 5 minutes**	**The vehicle can only downlink while on the surface of the water, which is not the environment desired for study, so the time spent downlinking must be limited**	**The vehicle successfully downlinks all of its data within 5 minutes**
038	**4.2**	**The system shall uplink data in 20 minute intervals for durations of up to 5 minutes**	**The vehicle can only uplink while on the surface of the water, which is not the environment desired for study, so the time spent uplinking must be limited**	**The vehicle successfully receives an uplink command within the five minute window**
039	4.2.1	The commands being uplinked shall not intefere with the data being downlinked from the vehicle	If uplink commands interfere with downlinked data, not all of the data will be received at the ground station	The same data packet will be sent twice, once while an uplink command is also being sent, and compared to ensure there are no differences
040	4.2.2	The vehicle shall produce a detectable response to commands being sent to it	This detectable response is the simplest way to ensure the uplink was successful	The ground station receives a confirmation after a command is uplinked

Functional requirement 4.2 describes the uplink window to the AUV, when commands are sent to it from our ground station. It flows down into design requirement 4.2.1, a directive that the commands being sent to the AUV must not interfere with the data being sent from the AUV, and design requirement 4.2.2, which indicates that the AUV must produce a detectable response to receiving commands. The former design requirement is to ensure data is handled well in the AUV while keeping utilization of the uplink/downlink window as efficient as possible. The latter design requirement is meant to aid in the testing process, to provide confirmation to the team that the AUV is receiving the commands the team is sending it.

3.2.5. Demonstration Requirements

Table 33: Requirement 5.1 Flow-down Matrix

ID	Assoc ID	Requirement	Motivation	Verification & Validation
041	***5***	***Demonstration Requirements***		
042	**5.1**	**The vehicle shall navigate on closed course no larger than 50 x 25 x 3.65 meters**	**A test volume greater than this would be difficult to find in Boulder**	**The dimensions of the test pool are less than these**
043	5.1.1	The vehicle shall detect and avoid the walls of a pool that meets this dimensional requirement	Collisions with the walls of the pool could damage the AUV	The vehicle creates a mask of the wall and steers to avoid a collision
044	5.1.2	The vehicle shall be able to navigate an underwater course of our design	The vehicle needs to be able to move about in an environment it is unaware of before the mission	The vehicle successfully navigates to each POI in the course
045	5.1.2.1	The course shall contain points of interest for the vehicle to find	A course containing POI will allow the AUV to demonstrate it can recognize objects in an unknown environment	At least one point of interest is present within the test environment

Functional requirement 5.1 describes the volume of water the AUV is to navigate in. It flows down into design requirement 5.1.1, which mandates the AUV must be able to detect and avoid the walls of the test volume and design requirement 5.1.2, which describes how the AUV will navigate a course the team designs and places into the volume: 5.1.2 flows down further into design requirement 5.1.2.1, which specifies that the course will contain points of interest for the AUV to locate. 5.1.1 further cements that the AUV must be capable enough at collision avoidance to not hit the walls and floor of the pool to avoid damage. 5.1.2 specifies that the team will have control over the design of the course the AUV will eventually navigate per a discussion with Lockheed Martin, and 5.1.2.1 clarifies that the course will contain objects for the AUV to find, which informs how the team will go about laying out the course and programming the AUV.

Table 34: Requirement 5.2 Flow-down Matrix

ID	Assoc ID	Requirement	Motivation	Verification & Validation
046	**5.2**	**The vehicle shall mark points of interest**	**The ability to differentiate objects within the surroundings will make observing the data easier for the ground station operator**	**A set number of points of interest will be included in the pool, and the vehicle correctly identifies all of them**
047	5.2.1	All data shall be retrievable from onboard storage for analysis	If any data is lost during downlink, it will still be usable if it can be retrieved from the vehicle itself	The data received by the ground station is also on the vehicle after the end of the mission

Functional requirement 5.2 describes that the AUV will mark points of interest, and design requirement 5.2.1 states that all point of interest data must be retrievable for analysis. This requirement is purely for our testing and debugging the AUV: to be able to see how it perceives the points of interest will be valuable as the team tunes the object identification software.

Table 35: Requirements 5.3-5.4 Flow-down Matrix

ID	Assoc ID	Requirement	Motivation	Verification & Validation
048	**5.3**	**The vehicle shall withstand impact to surface of body of water from 0.77 m above surface**	**Conceptually on a Europa mission, the AUV may be dropped into the ocean from a lander**	**The AUV can be dropped into the pool without compromising the structure**
049	5.3.1	The vehicle shall be constructed to endure external structural loads experienced during a collision at maximum operational speed	The AUV needs to move slowly enough and be sturdy enough to survive unexpected collisions	The AUV can survive impacting the pool wall at max operating speed
050	**5.4**	**The vehicle shall be recoverable**	**AUV must be recoverable to be reused**	**The vehicle is recovered without demanding effort or hardware**

Functional requirement 5.3 describes the maximum load case that the AUV must be able to withstand while still functioning to specifications. Design requirement 5.3.1 expands on this requirement to include collisions from other angles that may occur once under the water. However this requirement does not demand optimal performance after such a collision because these are unlikely to occur.

3.2.6. Safety Requirements

Table 36: Requirements 6.1-6.5 Flow-down Matrix

ID	Assoc ID	Requirement	Motivation	Verification & Validation
051	***6***	***Safety Requirements***		
052	**6.1**	**The vehicle shall prevent electrical discharge**	**Safety of all participants is the first priority**	**The current will be measured to be zero between the AUV and the water while the AUV is turned on**
053	**6.2**	**The vehicle shall prevent circuit overloads**	**Circuit overloads could destroy the electronics system and other sensors**	**All parts of the electronics system have overload protections**
054	**6.3**	**The vehicle shall not leak environmentally hazardous materials**	**Safety of all participants is the first priority**	**The AUV does not leave a chemical trail**
055	**6.4**	**The vehicle shall pass a customer safety inspection**	**Safety of all participants is the first priority**	**Passes customer safety inspection**
056	**6.5**	**The vehicle shall meet the MIL-STD-1472G for 5-95% male and female to 1 meter**	**The AUV needs to be easily transportable for safety**	**The AUV will meet all MIL-STD-1472G specifications**

ID	Assoc ID	Requirement	Motivation	Verification & Validation
057	6.5.1	The vehicle shall weigh no more than 20 kg	The vehicle needs to be light enough to be carried by a human being, meeting the MIL-STD-1472G for 5-95% male and female to 3 feet	The AUV will be weighed, ensuring the mass does not exceed 20 kg

Functional requirement 6.5 defines the MIL-SPEC for mass that the AUV must meet: design requirement 6.5.1 clarifies exactly what mass will be allowable under that MIL-SPEC. This ensures that the team has a clear way of validating that the AUV does not exceed the maximum mass allowable under this MIL-SPEC.

Table 37: Requirements 6.6-6.8 Flow-down Matrix

ID	Assoc ID	Requirement	Motivation	Verification & Validation
058	**6.6**	**The vehicle shall incorporate a kill switch**	**A kill switch ensures safety of the AUV and the team**	**The AUV has an operational kill switch**
059	6.6.1	The kill switch shall be activated by water breach and temperature	Excessive temperature and water can damage electronics	Test internal temperature sensors and leak sensors activate cut power to electronics
060	6.6.2	The kill switch shall cut power to all subsystems and surface the vehicle	The AUV surfaces for the safety of the vehicle and ease of retrieval	Ensure AUV is positively buoyant and power indication lights are off on kill switch activation
061	**6.7**	**The vehicle shall possess safety labels and markings**	**Safety of all participants is the first priority**	**All safety switches and hazardous components will have safety labels and markings**
062	**6.8**	**The vehicle shall be no larger than 2' x 2' x 2'**	**Ability to fit within standard payload volume**	**Measure dimensions**

Functional requirement 6.6 introduces the kill switch system to be used in the AUV. Design requirement 6.6.1 specifies that the kill switch will automatically activate in the cases of water intrusion and the temperature limit being exceeded. Design requirement 6.6.2 describes the functionality of the kill switch system, which is to completely depower the AUV. The former ensures that should the AUV find itself posed with these two destructive scenarios, it will protect itself against damage. The latter describes how the kill switch will protect the vehicle: the team agreed that in the event things begin to go awry, the AUV should allow itself to float to the surface whilst keeping the temperature from rising any further or anything shorting out: this meant removing all power from the electronics.

3.3. System Architecture

The baseline design of the AUV that will complete the mission and meet all functional requirements can be seen in Fig. 10 and 11 below.

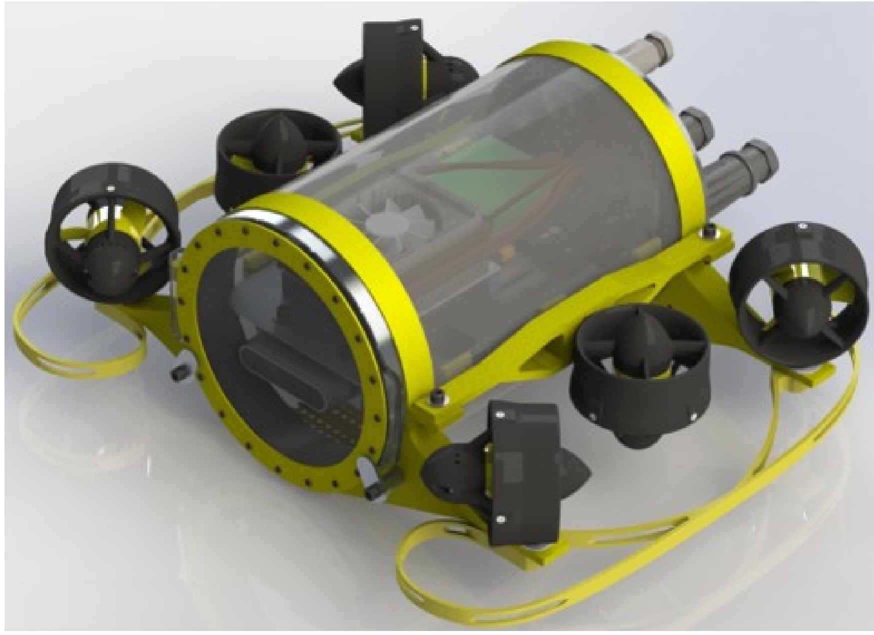

Figure 10: Isometric View of YELLOW Submarine

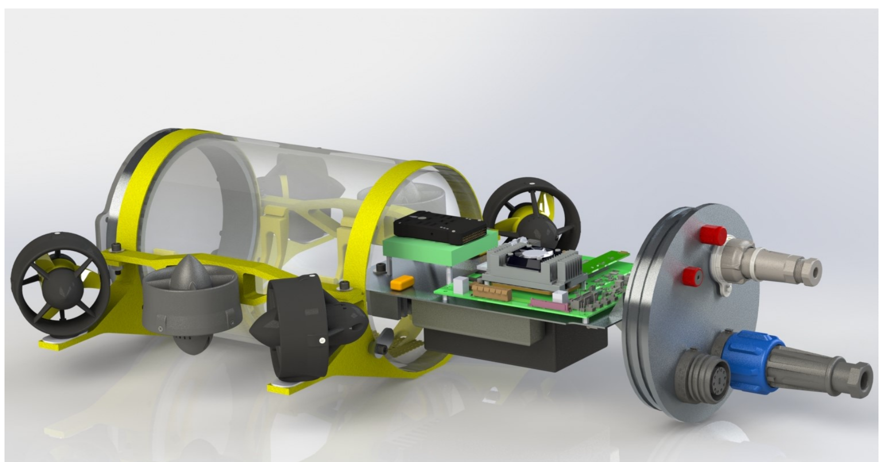

Figure 11: Disassembled YELLOW Submarine

The AUV will have a Non-Torpedo motor layout with 5 DOF. This consists of four horizontal motors controlling yaw, forward and lateral motion, and two vertical motors controlling roll and and vertical motion. The sub will have a cylindrical dry space containing all on board electronics including the computer, camera, and battery. The AUV will navigate and observe its environment using a D435 Intel RealSense camera located on the front face of the structure and process the environmental data identifying POI and obstacles on the on-board computer, a Nvidia Jetson TX2. This will communicate with a Pixhawk microcontroller that will send control commands to the motors in order navigate the environment. All electronics will be on a raised tray within the dry space that slides in and out of the AUV with the removal of the back plate.

Some key parameters of the AUV are as follows. The AUV will have a mass of 12.6 kg and be positively buoyant at a force of 124.6 N. The AUV will be 19.3 inches wide, 13.3 inches long and 8.2 inches tall. The depth sensing camera will capture video at 30 fps, have a visual range of 0.61-4.27 m, and a field of view of 50 degrees. The maximum operating temperature of the AUV is 333 K or 60 °C. The AUV will require 70 W of power, 6.5 A, and a power capacity of 8.9 Ah.

3.3.1. Mechanical

The mechanical design of the AUV consists of the AUV dry space, motors, and exterior frame structure. The motor configuration was selected using the results of the trade studies conducted at the beginning of the project. The six motors were arranged in such a way that the AUV would have active control in all directions except pitch. Because of this, the AUV needed to be designed such that it would be naturally stable in pitch. The condition for static stability in AUVs is that the center of buoyancy (CB) is above the center of gravity (CG). Since nearly all of the buoyancy is provided by the tube, it was assumed that the center of buoyancy would be located at the center of the tube. Thus, to achieve static stability, the center of gravity needed to be located below the center of the tube. By attaching the battery, which is the heaviest component, to the bottom of the electronics tray, it was determined using SolidWorks that the CG would lie 0.0127 m below the CB, making the design statically stable. In the event that the CG needed to be lower, the lead weights inside the tube used to achieve the desired mass could be moved lower in the tube to lower the CG. To predict whether the design would be dynamically stable in pitch, a model was developed using the free body diagram below.

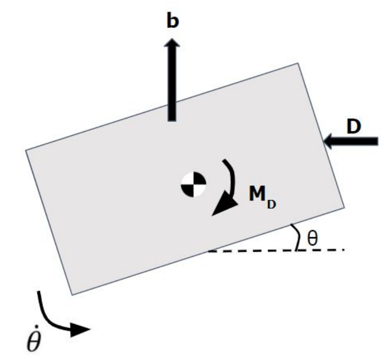

Figure 12: Pitch Stability Model FBD

Summing the moments about the CG and rearranging gives the following second-order differential equation for pitch angle.

$$\ddot{\theta} = \frac{\frac{1}{2}\rho(-\dot{\theta})|\dot{\theta}|S C_{D,ang} + \frac{1}{2}\rho V^2 S C_{D,front} x_p \theta - b y_b \theta}{I_{AUV} + I_{add}} \quad (1)$$

Integrating Eq. 1 with ODE45 in MATLAB using a 5 degree initial disturbance gives the following plot.

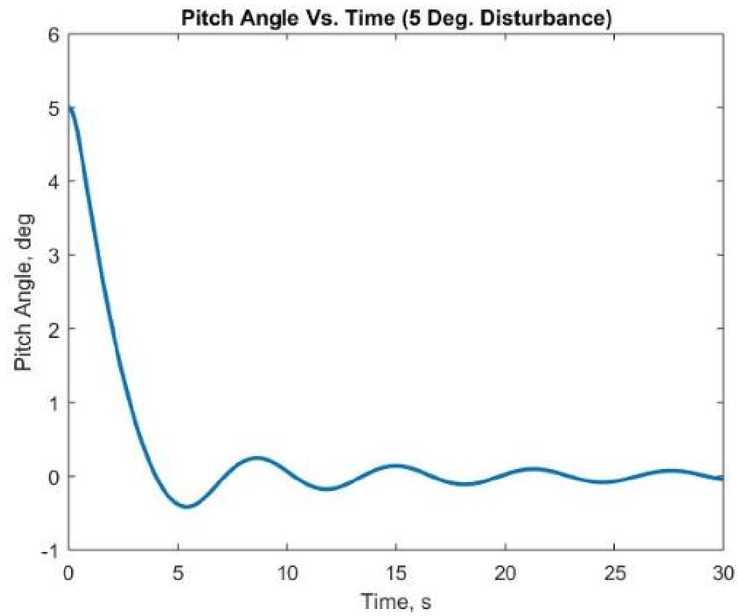

Figure 13: Pitch Stability Model Predictions

Fig. 13 shows that the AUV design is both statically and dynamically stable in pitch.

The AUV dry space consists of an acrylic tube sealed on both ends by endcaps. The rear endcap is aluminum with bulkhead wire connectors to allow wires from external components such as the motors to pass into the dry space and still remain watertight. It is sealed by 2 static radial O-rings to ensure no water reaches the inside of the tube.

Since the AUV uses a camera for image processing, the front endcap needed to be transparent. As a result, the front endcap consists of an aluminum ring with a clear acrylic plate. The ring is sealed against the tube using 2 static radial O-rings and the acrylic plate is sealed against the aluminum ring using a rubber gasket.

The aluminum structure around the AUV serves to hold the components in place and provide a moment arm for the motors. The overall design of the structure was selected to provide ease of manufacturing, and the cross-section dimensions of the motor arms were determined using a theoretical model. Requirement 5.3 mandates that the AUV must survive an impact to the surface of the water from a drop height of 0.77 m. Using conservation of energy and the impulse-momentum theorem, it was determined that the maximum impact force the AUV would sustain would be 3924 N. Next, a beam bending model was used to predict the stress in the motor arms. It was assumed that the impact force is distributed through the external components relative to their area. For example, since the motor arm is 2.53% of the AUV's bottom area, it will experience 2.53% of the impact force. This gives a distributed load w = 325.7 N/m acting on the motor arm and a point load P_m = 137.7 N acting at the end of the motor arm where the motor impacts the water. The free body diagram used to derive the beam bending model is shown below.

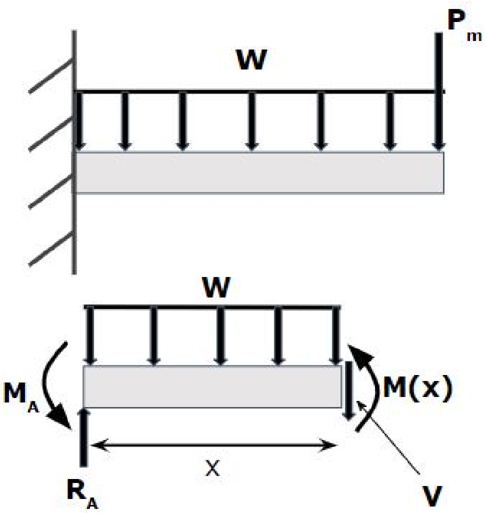

Figure 14: Beam Bending Model FBD

Solving for the support reactions and summing the moments about point x gives the following equation.

$$M(x) = -w\frac{x^2}{2} + wLx + P_m x - LP_m - w\frac{L^2}{2} \tag{2}$$

Eq. 2 was then plotted in MATLAB to obtain the following figure.

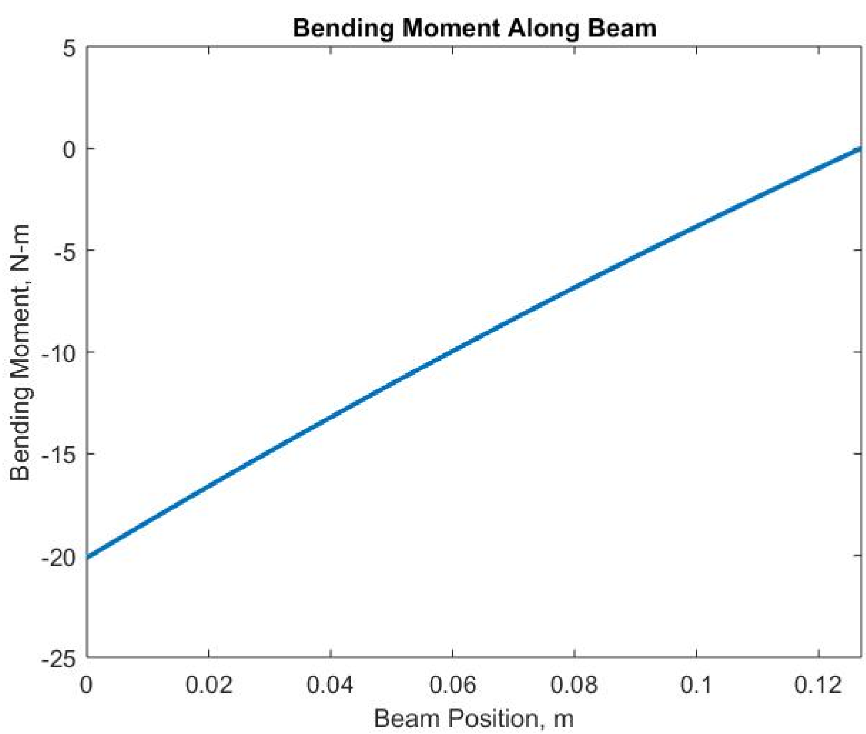

Figure 15: Internal Bending Moment Along Motor Arm

Fig. 15 shows that the maximum bending moment in the motor arm is 20.11 N-m. With this value, the maximum internal bending moment can be calculated from

$$\sigma_{max} = \frac{M_{max}}{S} \tag{3}$$

where S is the elastic section modulus of the member. For a rectangular cross-section, this is given by

$$S = \frac{1}{6}bh^2 \tag{4}$$

where b is the width of the beam and h is the thickness. The dimensions selected for YELLOW Submarine's motor arms were b = 0.0254 m and h = 0.00635 m. With these dimensions, the section modulus is $S = 1.707 * 10^{-7}$ m^3 and the maximum stress is $\sigma_{max} = 118$ MPa. This is well below the design stress of $\sigma_{design} = 180$ MPa, which is from aluminum 6061-T6511 and a factor of safety of 1.5. Thus, the dimensions and material selected for the external frame are suitable for the given mission.

A driving factor for multiple other design choices revolves around the buoyancy of the AUV. It had always been decided that the AUV must be positively buoyant in order to allow it to surface on its own without power. This idea is especially crucial for Requirement 6.6 which states that vehicle must have a kill switch. The kill switch will currently cut power to all electronics except for the vertical motors. The vertical motors will produce a thrust that causes the AUV to ascend more rapidly; however, in the event that the vertical motors had failed, the AUV will still eventually rise to the top due to the positive buoyancy.

Having the AUV positively buoyant came at a cost though, as the vertical thrusters will have to be constantly running to keep the AUV at a constant depth. This is basically an artificial way to make the AUV neutrally buoyant while it is in operation. To limit the power draw, the two vertical thrusters need to be running at the minimum thrust output of 0.5 N each[2]. Essentially, the AUV will only have 1 N of positive buoyancy.

Starting with a free body diagram, depicted by Fig. 16, a force balance must be completed. Buoyancy force is defined as the volume displaced times the density of the fluid times gravity (Eq. 5). The weight is simply mass times gravity (Eq. 6) and thruster force is the output force provided by the thrusters.

$$F_{buoyancy} = \rho g V_{disp} \tag{5}$$

$$F_{weight} = mg \tag{6}$$

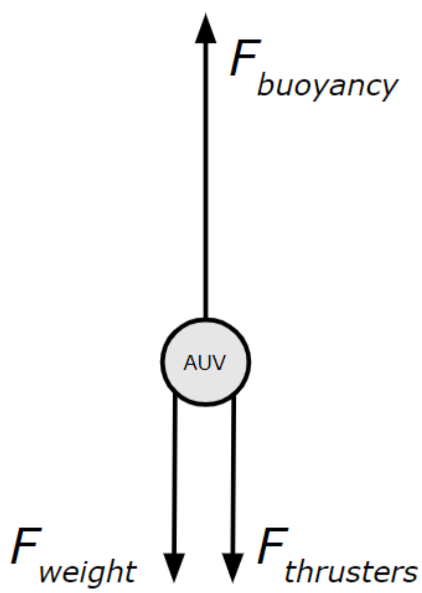

Figure 16: Free Body Diagram for Buoyancy

Implementing a summation of forces using Eqs. 5 & 6 with thruster force, and rearranging to make thrust required as a function of mass yields:

$$F_{thruster} = F_{buoyancy} - F_{weight}$$

$$F_{thruster} = \rho g V_{disp} - mg \tag{7}$$

Using this equation and varying masses and thruster forces, a buoyancy model for the AUV was modeled as seen in Fig. 17. It was determined that the AUV did not need additional ballast and would meet its 1 N of positive buoyancy requirement at a mass of 12.6 kg. During testing, it would be easy to change the mass in case the model was incorrect. There are additional lead weights nested inside of the AUV that can be increased or decreased accordingly.

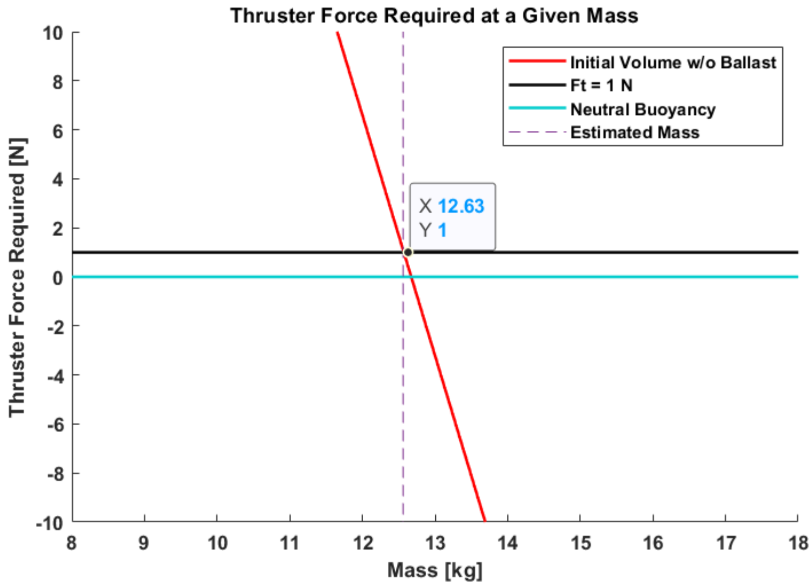

Figure 17: Thruster Force Required as a Function of Mass without Ballast

The temperature inside of the compartment is a large risk of this project and is a requirement defined by Requirement 1.6. The major risk revolves around the maximum operating temperature that the electronics can operate at. If the internal temperature reached a level higher than the maximum operating temperature, then the electronics would no longer be able to function and the AUV would not work as intended. Thus, a complex thermal rejection system was created to mitigate this risk.

The thermodynamic model was made via a resistance network. This is a common way to determine the overall heat transfer through a series of elements; in this case, combined convection and radiation to the air with conduction through the electronics tray and thermal straps, conduction through the housing walls/endcaps, and combined convection and radiation to the water.

At first, the thermal rejection system consisted of only forced convection moving air over the aluminum rear endcap heat sink. However, preliminary models were showing that the margin was only 10K and was deemed unsatisfactory. With this in mind, thermal heat straps were added. The thermal straps in the upper half of the compartment would run from a copper housing surrounding the Xavier to a copper block on the aluminum end cap, while the lower half of the compartment thermal straps would run from the batteries to the aluminum end cap. Utilizing this new thermal rejection system, the margin increased from 10K to 27K (an increase from 18°F margin to 49°F margin). A rendering of these thermal straps can be seen in Fig. 18, represented by the copper colored wires running down the center of the electronics tray.

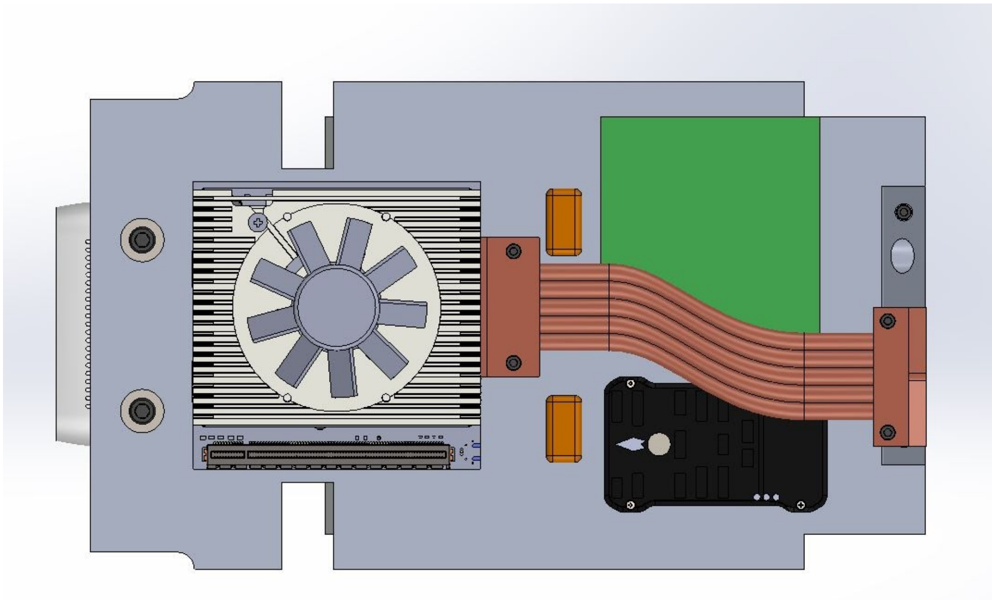

Figure 18: Top View Rendering of Electronics Tray with Thermal Straps

Heat transfer will increase with a larger temperature difference between the inside of the housing and the pool. To model the steady state temperature, the pool temperature was set to the standard upper bound temperature for the demonstration pool, T_{pool} = 300K (27°C). Utilizing the thermodynamic resistance network, a model showing the different values of heat transfer rejected from the housing can be seen in Fig. 19.

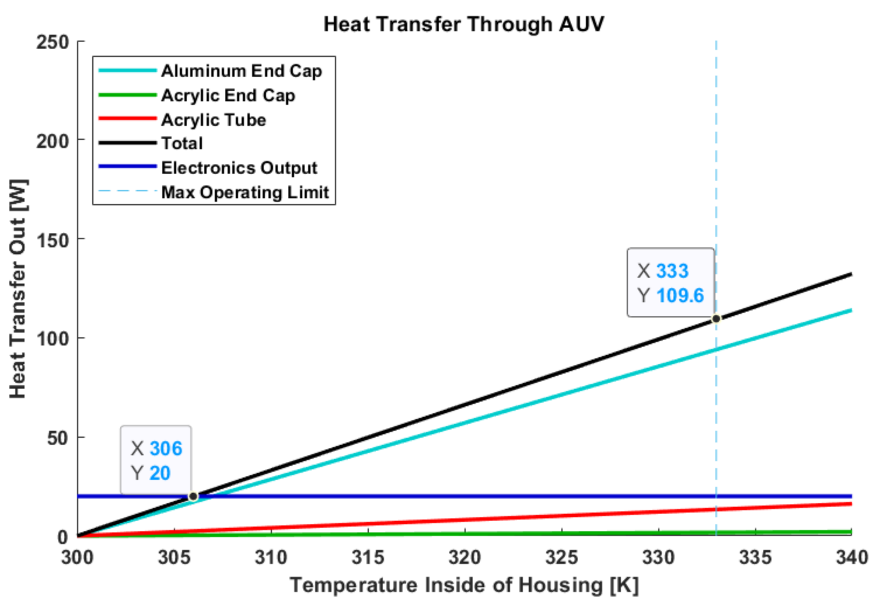

Figure 19: Heat Transfer Out and Steady State Temperature

The electronics total heat output is roughly 20W and is represented by the dark blue line. The steady state temperature, T_{ss}, can be found from the intersection between the total heat output and the electronics heat output. From Fig. 19, T_{ss} = 306K for the internal housing based on the worst-case scenario. This value left plenty of margin between the steady state and maximum operating temperatures in the event that the electronics ran warmer than expected. Also, notice that the graph starts at 300K, which is the steady state temperature of the pool. The steady state temperature out of the AUV cannot be lower than the steady state temperature of the pool. If this were the case, then the pool would be injecting heat to the housing. Below in Table 38 are the maximum operating temperatures for the most important electronic components. The lowest maximum operating temperature is the battery, which can operate at a temperature of up to 333K. Referring back to Fig. 19, the vertical dotted line on the right shows this maximum operating temperature.

Table 38: Maximum Operating Temperatures for Major Electronic Components

Component	Max Operating Temperature
Battery	333K (60°C)
Intel Realsense D435	343K (70°C)
Nvidia Jetson Xavier	353K (80°C)
Pixhawk	358K (85°C)
PCB	383K (110°C)
ESC	413K (140°C)

3.3.2. Electrical

The electrical and hardware subsystem design includes the power system, environmental sensors, and organization and integration of all hardware within the AUV. An interconnect diagram of the AUV's electrical system is shown in Fig. 20 below. It outlines each hardware component and how it is connected to the system.

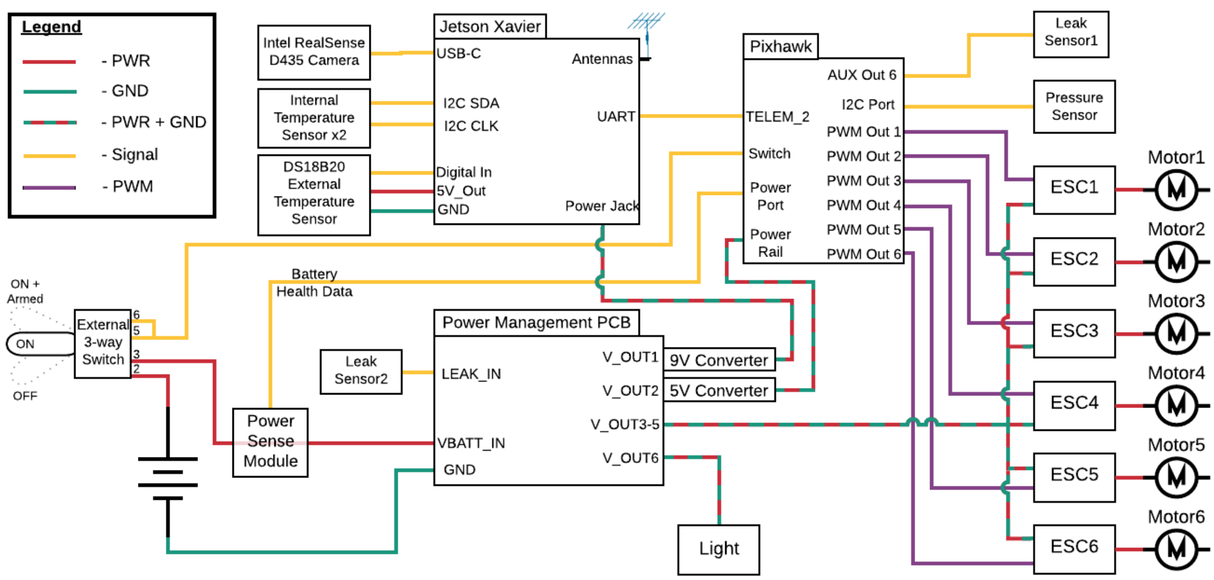

Figure 20: Interconnect Diagram

The AUV power system consists of a battery chosen to meet power budget requirements, a custom printed circuit board, (PCB) to distribute power to necessary components and kill power when a severe leak is detected. The battery chosen, a 12.8V 12Ah lithium iron phosphate battery meets the power requirement to power all components of the AUV for the entire duration of the mission. The required power and power budget were determined by the finding the current draw and peak power of all electrical components. Then the mission is split into three separate states of power draw: translating, rotating, and communicating. In each of these states there are different components running at various power ratings. Next, each state is given a weighting based on how much time is spent in that state. A weighted average is taken from all three states and added up to give a total weighted average for power and current. The average total current is then used to determine the total power consumption during the one hour mission, assuming a converter efficiency of 90%. Finally, accounting for a depth of discharge of 75% and design margin of 1.2, it can be seen in Fig. 21 that a minimum battery capacity of 11.9 Ah is required.

Vehicle State	Current (A)	Power (W)	Time Spent in State (hrs)	Weighted Average Total Current (A)	Weighted Average Total Power (W)
Translating	8.175	83.7	0.45	3.679	37.67
Communicating	4.713	38.7	0.25	1.178	9.680
Rotating	6.636	63.7	0.30	1.991	19.116
Total:			1.00	**6.85**	**66.5**
Battery Characteristics				**Peak Current (A)**	**Peak Power (W)**
Voltage (V)	13			**8.17**	**83.7**
Depth of Discharge	0.75				
Temperature Correction Factor	1			**Total Consumption (Ah)**	**Battery capacity required (Ah)**
Design Margin	1.2			7.44	**11.9**
Regulator Characteristics					
Efficiency	0.92				

Figure 21: Power Budget

The custom PCB was designed to distribute power from the battery to the required electronics and to cut off power when a leak is detected. There were leak sensors located at the bottom of the vehicle at two heights. One touching the bottom that commands the vehicle to end the mission and surface if a small leak is detected. The second is elevated to determine if there is a major leak in which it would cut power to all electronics to minimize damage. The design schematic for the PCB can be seen in Fig. 22. The AUV communicates with the ground station using WiFi through the onboard computer.

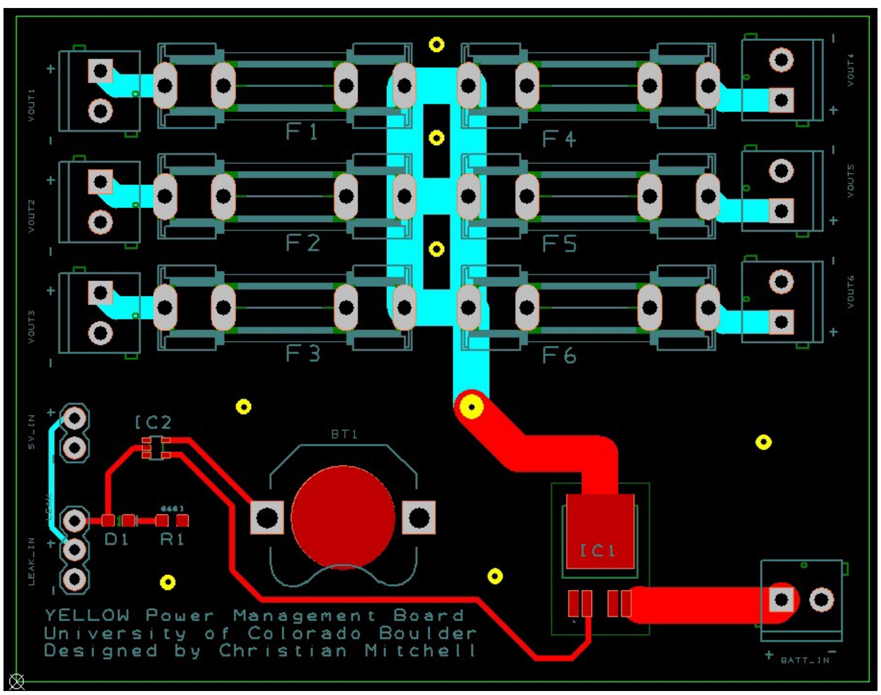

Figure 22: PCB Schematic

3.3.3. Software

The software was required to ensure the AUV could complete its mission with essentially no human input. This required using image processing to detect objects in the field of view of the camera, making decisions about where to go based on the image data, and activating the motors appropriately. We also had to periodically downlink data to a ground station (laptop).

The primary sensors that controlled the AUV were the D435 stereo-depth camera and the pressure-depth sensor.

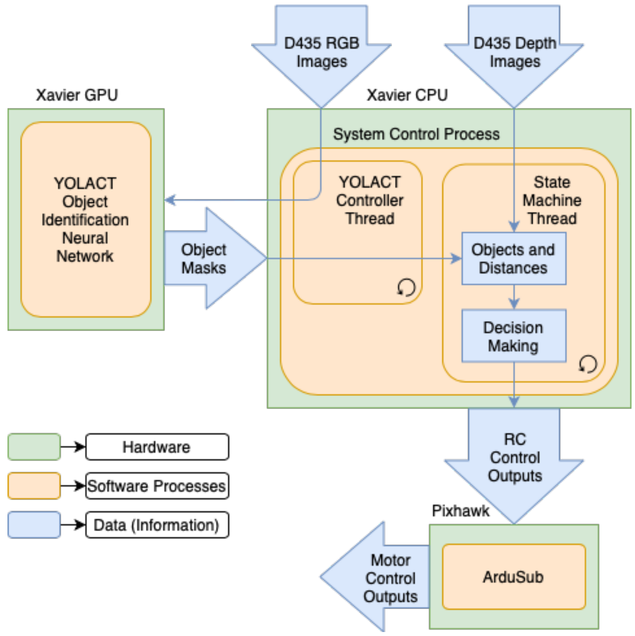

Figure 23: Data Flow Diagram

The pressure depth sensor allowed us to determine how far underwater we were. The stereo-depth camera provided two images: a color image and a distance image. The distance image was created in the same way our brains determine distance: using two cameras a fixed distance apart. The color image was fed into an image-processing system to determine what objects (if any) were in the field of view of the camera. The object masks (the set of pixels that make up the object) were then overlaid on top of the depth image. The net result was a list of objects, their locations within the field of view of the camera, and the distances to each of them. Using this data, the AUV used a state machine to determine what course of action to take (move forward, rotate right, etc.) and sent those commands to the ArduSub control system on board the neighboring single-board computer (SBC), the Pixhawk. This SBC used an on-board IMU and the pressure-depth data to stabilize the AUV, maintain depth, and provide control.

4. Manufacturing

Forrest Barnes, Benjamin Bruce, Alexander Gill, Danny Liebert, Matthew Ryan, Micah Zhang

4.1. Mechanical

4.1.1. Purchased Parts

In order to complete the physical structure of the AUV some components were purchased, while many were manufactured. Of the parts that were purchased, the largest was the acrylic tube that made up the interior dry space. This was an 8 in. outer diameter, 12 in. long, 0.25 in. thick custom acrylic tube purchased from Colorado Plastic Products. Other than that, the only other parts that were purchased were all the fasteners (including nuts, bolts, washers, o-rings, etc), and the bulkhead wire connectors. The rest of the mechanical components were all manufactured.

4.1.2. Manufactured Parts - Metallics

The AUV is comprised of an aluminum exterior structure. Several other metal parts were also used on the inside of the dryspace. Manufacturing the physical components of the AUV was one of the largest tasks second semester. This resulted in the major manufacturing operations using manual mills, manual lathes, and CNC milling.

Starting with the endcaps, both the front bulkhead and rear endcap required using a manual lathe due to the large size of the pieces. Both parts started as 8.5 in. diameter, 3 in. long aluminum stock. First turning the parts down to the appropriate diameter and facing the front, the o-ring glands are the next step. This was the most difficult operation as the o-ring manufacturer calls for some very tight tolerances for the glands. These can be seen in Fig 46. Although matching the given tolerances were attempted, it was found to be easier to remove a very small amount of material at a time and test fit the endcaps with o-rings onto the tube until a desired fit was reached. This was easier to do because the parts were able to stay in the lathe during this process. With the o-ring glands finished, the centers were bored out, partially for the rear endcap, and fully through for the front bulkhead. Lathe work complete, both parts now required holes to be milled: 20 holes drilled and tapped on the front bulkhead to fasten the acrylic and gasket, and several larger holes on the rear for all the wire passthroughs. This involved creating a 2D CNC path to accurately drill all the necessary holes. Each part took roughly 15-20 hours of machine time to manufacture.

Continuing with the aluminum exterior structure, the bottom clamps/horizontal motor mounts were manufactured with a 3 axis CNC. These two parts are roughly 18 in. long, 5 in. wide and cut from 1 in. thick 6061 aluminum. The drawing of this part can be seen in Fig 47. This part required the use of SolidCAM to create the 3D tool paths to run the CNC mill. Because of the thickness of the material, each pass around the profile of the part required a relatively small step down until the full depth is reached. This slow, but necessary process resulted in the machining of the part to take longer than expected. However, the CAM software was much easier and quicker to use than expected and balanced out the overall time of these parts. After the CNC operations were complete, holes were drilled into the arms for the motor mounts holes tapped for clips the part is complete. Overall, the two parts took roughly 6-8 hours each to complete.

Similar to the bottom clamps, the vertical motor mounts were manufactured the same way. Started by producing a 3D tool path for the CNC, and using the same technique as before. These parts, being a little smaller took only 2-4 hours each to manufacture. A drawing of this part can been seen in Fig 48.

Completing the major exterior structural parts are the top clamps, Fig 49. These are 1 in. wide strips of 1/16 in. aluminum. The strip was rolled to match the top half of the tube, and bent at a 90 degree angle where the top clamp will meet the bottom clamp. The rolling process was performed slowly and referenced often to the tube until the proper shape was achieved, leaving plenty of extra on either end to perform the bend. These parts were planned to be manufactured using 5052 aluminum which bends easier, however in the rush to complete as much manufacturing as possible before the project was halted these were made using 6061 aluminum. The part was completed just fine however did require heating the aluminum for the sharp 90 degree bend to prevent the aluminum from stretching apart. These parts took approximately 1-2 hours each to make.

The rest of the AUV's metal components were manufactured using the water jet. This includes the electronics tray, motor shims, and the endcap clips. These were made with a 1/16 in. sheet of aluminum 6061. The water jet is operated by using the Wazer cutting software. All of these parts took roughly 2 hours to manufacture.

There are several more metal components that were to be manufactured: Camera mount, electronics tray mount, xavier heat sink, endcap heat block, and endcap clip spacers. These will be discussed in further detail in the appendix.

4.1.3. Manufactured Parts - Non-Metallics

Even though most of the AUV's structure is made of metal, several important components are manufactured with other materials. First of which is the clear front acrylic panel. This was manufactured by laser cutting a 0.25 in. sheet to match the diameter of the tube, and 20 through holes for the bolts to pass through. There is also a tab on either side to act as hand holds when taking the front bulkhead off. Between the acrylic plate and the aluminum front bulkhead is a rubber gasket to ensure an appropriate seal. This was cut by hand using a knife to match the profile and allow the bolts to pass through.

All other Mechanical components of the AUV were to be 3D printed. This included the electronics tray mounts, water baffle (splash guard) at the bottom of the interior, and the bumpers. The reason these parts were chose to be 3D printed are for a few reasons. For the electronic tray mounts, these did not need to be extremely strong, and they way they were designed they would be strengthened by their shape and their location in the tube. This led to quick and easy 3D printing. As for the water baffle, this was completely non-structural and therefore the quick turnaround of a 3D print was perfect. Finally the bumpers were the most complex print. Due to their large size these took the longest to print. It was chosen to manufacture the bumpers this way because the team concluded that since the AUV would not be traveling very fast, any impact would be minor. However, if there was to be a larger impact, these bumpers could efficiently absorb the load, because they were designed to flex, or even simply break, as the intended point of failure to protect the AUV. Furthermore, these were easily to manufacture and could always have spares at the ready.

4.2. Electrical

Manufacturing the electrical subsystem was primarily a task of integrating a significant number of purchased sensors, computers, and other parts. The one element that involved more manufacture than wiring was the PCB and associated power distribution components.

4.2.1. Parts Purchased

In the electrical subsystem, all of the following components were purchased. For the image processing system on the AUV, components included the Jeston Xavier single board computer and the D435 depth-sensing camera. The SBC was also used in the control loop, along with the Pixhawk microcontroller, pressure sensor, pressure sensor wire passthrough, 6 ESCs, 6 thrusters, and 2 large thruster wire passthroughs. The power system included a 12Ah battery, a 9V switching converter, a 5V switching converter, and various PCB components. Safety measures connected to this system included a 3-way switch, 2 internal thermocouples, 2 leak sensors, and 6 fuses. Additional components to fulfill other functional requirements included an external thermocouple, an additional passthrough, and a front light which had yet to be purchased. To speed up development and testing, an extra battery, the smaller Jetson Nano SBC, and an electronic dummy load were also acquired. Backups were purchased or planned in the budget for a number of these components.

4.2.2. PCB Manufacture

The PCB was the only component of the electrical subsystem that was custom manufactured. To have this piece manufactured, the design schematic of all traces and holes in the board was sent to 4PCB and ordered. Once it arrived, each component was hand-soldered onto the board. This included a number of header pins, 7 screw terminals, a NOT gate, a coin battery holder, a power switch, and 6 fuse holders, all of which were purchased. The PCB schematic, Fig. 22, shows where each of these components were placed.

For the most part, soldering components to the PCB went well. However the NOT gate was particularly small and it proved difficult to keep the gate pins on the contacts in correct orientation while applying solder and removing the extra. Fortunately, the team was careful to not keep the hot soldering iron near the gate for too long and after multiple tries, the component was finally secured properly.

A second PCB, designed to fix problems encountered in testing with the first version, was also to be manufactured. This was to take place in the two weeks following project cessation. The second PCB would have been ordered, then hand-soldered in the same manner as the first.

4.2.3. Integration Plan

The integration plan for the electrical subsystem had a few parallel flows that converged near full system integration. The first of these was the motor control system. It began with soldering together the motors and ESCs. Due to large wire gauge, soldering these components was a bit messy, but connections were further secured by applying electrical tape. After these were tested with input signals from a waveform generator, they were integrated with the Pixhawk and Jetson Nano for software control response testing.

Meanwhile, integration for the power system was going on. This first involved integrating the voltage regulators with the power distribution PCB. After testing this, the leak sensors were added to the system and also thoroughly tested. Integration of these components went well, but some design issues arose when testing the leak sensors. Next, the PCB and regulators were integrated with the Jetson Nano, with power being supplied from a stable power supply, through the PCB and 9V regulator, and eventually powering the SBC. Using the appropriate connectors, this was an easy task. Finally, the battery, after much testing, was integrated into this system.

For the first systems test, the power system and motor control systems were to be integrated to create a nearly complete electrical subsystem. First, the motor and ESC wires were separated and connected into the 2 large wire passthroughs. This took longer than expected because there were a total of 36 wires to screw into these passthroughs and the wire openings were rather tight. Additionally, due to the construction of the passthoughs, the motor wires had to be disconnected, run through the large end cap, and reconnected to the passthrough terminals on the inner side of the end cap. The ESCs and the Pixhawk were then arranged and temporarily secured on the electronics tray. This was very difficult due to short wire lengths, but was overcome by rearranging some of the planned electronics tray layout. Unfortunately, this also involved rearranging all of the wires in the passthroughs. Once that was complete, the Jetson Nano and power system was connected Pixhawk and secured to the electronics tray.

The remaining integration tasks for the electronics subsystem included integrating the second version of the PCB, the pressure sensor, the thermocouples, the light, and the external kill switch. The Jetson Nano test SBC was also going to be replaced with the larger Jetson Xavier SBC and visual-depth camera, which made up the image processing system.

4.3. Software

4.3.1. Image Processing

The image processing consists of the integration between the D435 stereo-depth camera, the NVIDIA Jetson Xavier single-board-computer, and the YOLACT instance segmentation algorithm. The image processing subsystem provides the AUV with point of interest (POI) identification, spatial awareness, and basic localization capabilities.

The image processing system was nearly complete as of the project's cancellation. The image processing stack was fully implemented, allowing the AUV to recognize POIs (uniquely-colored pool buoys), select the pixels corresponding to each object, sample a subset of those points and extract their corresponding distance measurements from the depth maps, and produce a final distance estimate for each object detected. The end result was an image processing subsystem capable of estimating the relative distances of both POIs and pool walls within frame in real-time at 3.2 FPS. However, the image processing subsystem had yet to be trained to recognize objects that were farther than 3 meters away and new training designed to reduce confusion based on ripples on the surface of the water had not been fully tested. The team also created an auto-labeler to rapidly increase the size of the training dataset. This would allow for much greater accuracy in POI identification due to the ability to quickly label new test data and train the image processing system using it.

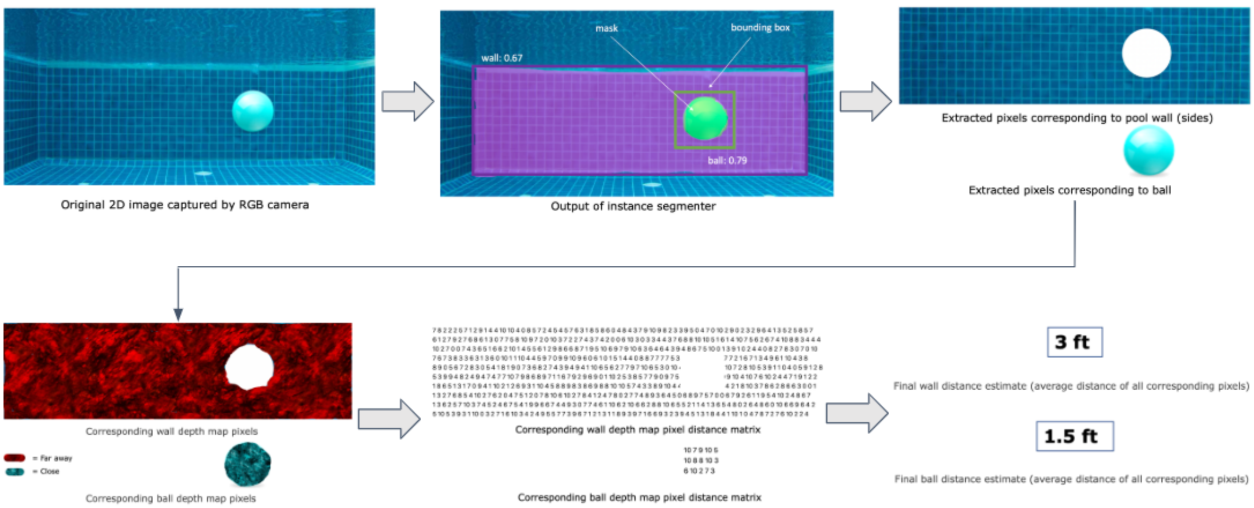

Figure 24: Planned Image Processing CONOPS

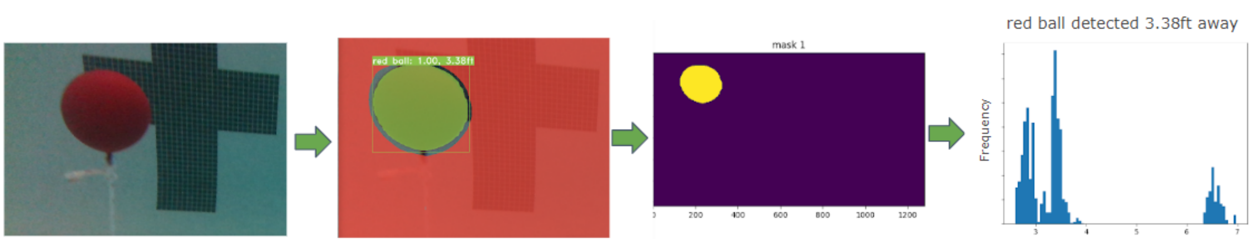

Figure 25: Actual Image Processing CONOPS

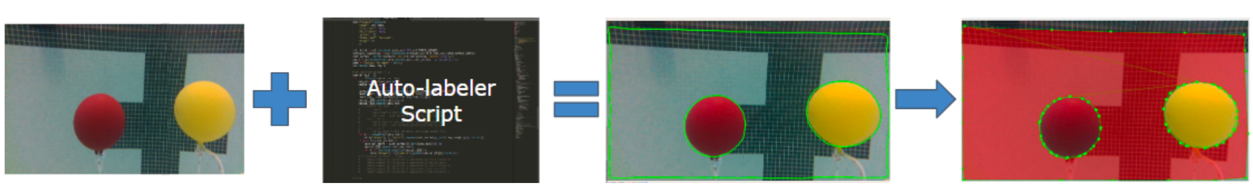

Figure 26: Auto-labeler Conops

4.3.2. Control System

The team elected to use the ArduSub motor control system on board the Pixhawk single-board computer to control the AUV. To test this system, the team created a simulation of the AUV in Gazebo. This simulation included the pool environment and imported buoyancy plugins to simulate the environment that the AUV would be tested in as accurately as possible. In order to simulate the environment as accurately as possible, a CAD model of YELLOW submarine was imported into gazebo, along with models of the blue ROV motors that were to be used on the AUV. By attaching these motors to the imported model in the designed orientation, along with setting the center of buoyancy and center of gravity according to their predicted locations, the team was able to model the most vital aspects to the functionality of the control system. ArduSub was then connected to the imported motors in the simulation to verify that it could create the desired control outputs. This test was successful, and verified that ArduSub could control the AUV. It also verified that the control outputs from ArduSub gave the control system the correct capabilities to achieve navigation objectives. Vertical, horizontal, yaw and roll motions were tested in the simulation, all of which produced expected results. The AUV was also shown to be stable in the simulation, as perturbations in the roll and pitch of the AUV corrected over time with no motor inputs. We also ran an out-of-water motor test to ensure that putting ArduSub on the Pixhawk didn't change anything. After a little debugging, this test also came out successful, and proved that we could control the AUV in real life as well. The team was able to run a script which tested all of ArduSub's control channels that were relevant to the motor configuration of the AUV. This test resulted in expected responses from all of the motors for each channel tested in Manual mode. We also tested ArduSub's STABILIZE mode by tipping the Pixhawk slightly around the roll axis. This test was also successful, as ArduSub counteracted this roll using the vertical thrusters.

4.3.3. State Machine

The state machine was designed to control every other process on the Xavier. It would take images in, pass them into the YOLACT image processing algorithm, integrate the image masks with the distance images to generate objects and distances (but not before passing another image into the YOLACT algorithm), make a decision about what to do based on all the data available, and pass that decision to ArduSub running on the Pixhawk. A general outline of the state machine's decision-making process is shown in figure 27. This decision-making process was modeled after our CONOPS. The AUV must dive, Rotate in place until it detects an object nearby, then Translate towards that object while keeping it within the field of view of the camera. Once the object is close enough, the AUV must Orbit the object while keeping it within the field of view of the camera. Once the AUV has completed one orbit of the object, it must Rotate in place again until it identifies another point of interest. At intervals of 20 minutes the AUV must also Resurface and transmit data back to a ground station. The state machine was in the process of being integrated with the image processing system when the project was cancelled. However the state machine was nearly complete at this point, with nearly all navigation processes fully implemented.

4.3.4. Ground Station

The ground station setup for the project is incredibly simple, and so the manufacturing requirements were also very simple. In order for the signal to be received while on the surface of the water, an antenna had to be attached to the on-board computer in order to connect to the WiFi router just outside of the test environment. The ground station computer will also be connected to this router. While internet access is unavailable, the two devices can communicate in this fashion. When the setup script is run on the ground station computer, it will install a key that allows the AUV to connect to it without requiring user input. This is all of the setup required for the ground station computer itself. For the AUV, the state machine is aware of the IP address of both itself and the ground station computer due to the fact that the router is consistent for all missions. As long as the key is setup on the ground station computer, the AUV can transfer its data to a preset directory on the ground station computer. In theory, due to its simple nature, data transfer should only take a few seconds.

5. Verification and Validation

Benjamin Bruce, Colin Claytor, Alexander Gill, Samuel Kersting, Griffith Kull, Christian Mitchell, Micah Zhang

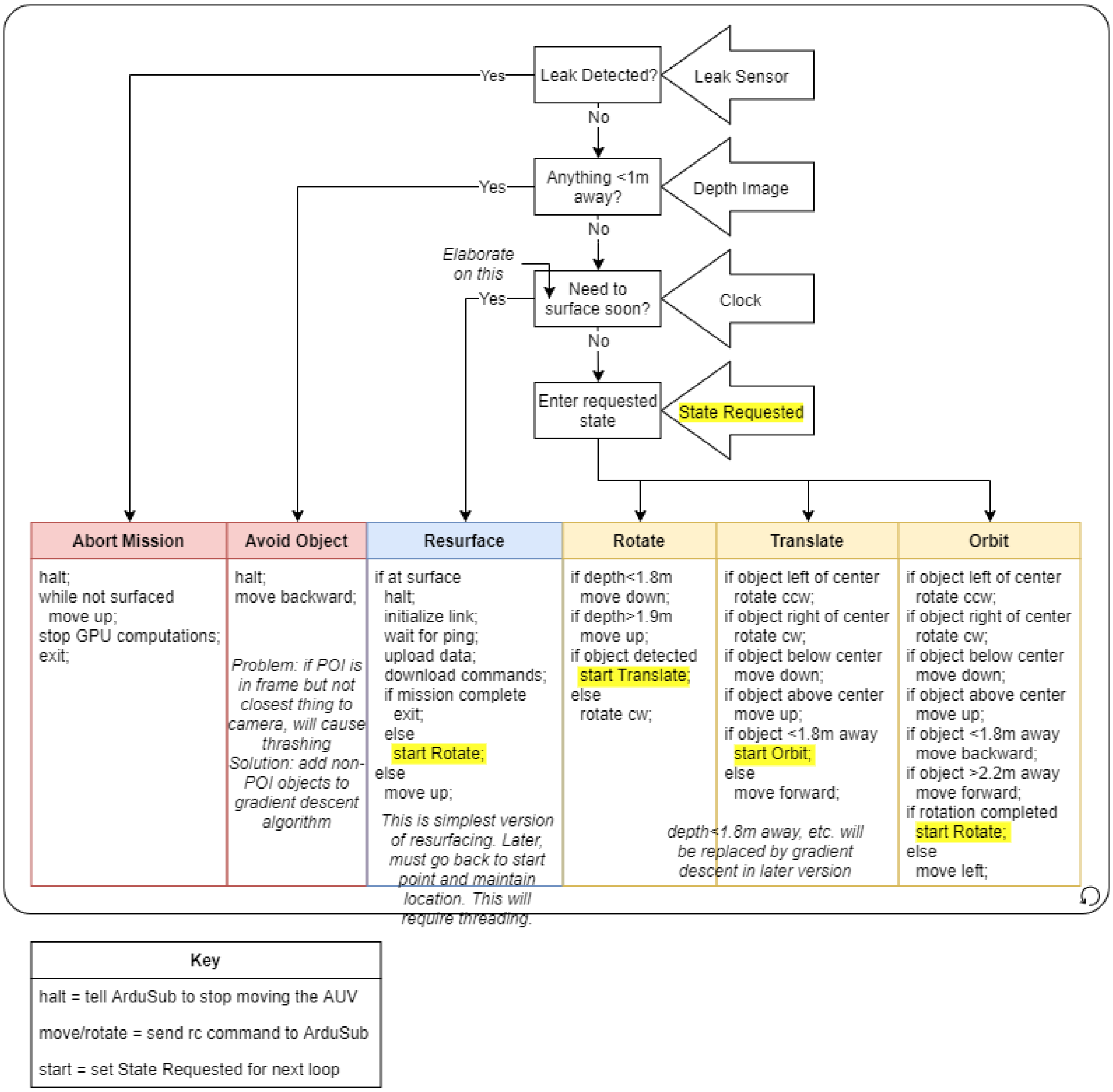

Figure 27: State Machine Diagram

5.1. Mechanical

5.1.1. Leak Test

Multiple leak tests have already taken place, where the main goal was to verify whether the design for a water-proof compartment was sound. By verifying the design, more breaches were able to be made to the compartment, such as the wire connectors in the rear aluminum end cap.

The leak test started with placing paper inside of the housing along the acrylic tube. This would be used to determine if any water did breach the compartment during the test, i.e. if the paper was wet, there was a leak. Next, weights would be either be placed inside or attached to the outside of the housing. Then, both endcaps would then be sealed onto the housing and the assembly would be submerged to the mission depth of 12ft for 15 minutes. After the 15 minutes, it would be retrieved and the paper would be examined for any moisture. If the paper remained dry, then the test would be successful.

Below are a few images of the test in progress. Fig. 28 shows the housing submerged at its operation depth. It is tied to a tether so it would be easily retrievable. Figs. 29 and 30 shows the paper lined inside of the housing to indicate whether there is a leak. Fig. 29 is pre-test where the paper is dry, while Fig. 30 shows the paper with moisture on it. This indicated that there was in fact a leak in the housing, which was determined to be from the gasket between the acrylic front plate and the aluminum endcap's mounting bracket. This was quickly remedied by using a different type of gasket and the first stages of the leak test were successful.

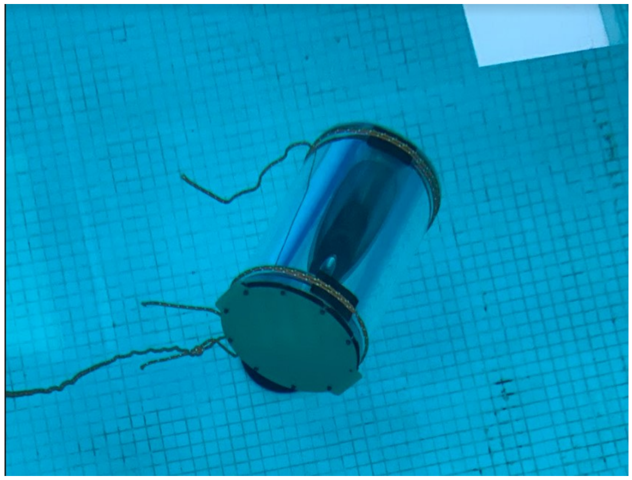

Figure 28: Housing Submerged at Operational Depth

Figure 29: Paper Lined Inside of Housing: Dry

Figure 30: Paper Lined Inside of Housing: Wet

Each time the main compartment was breached with an additional bulkhead connector, a leak test would take place to ensure the electronics were safe inside. Unfortunately, the project halted before the final leak tests were completed. The last leak test to take place was the first full systems test, seen in Fig. 31. In this test, there was a small leak through the bulkhead wire connectors. These leaks were most likely due to three wires inside of a circular tube, which would leave space in between the tube's edges and the wires themselves. The solution for this would be to fill the tube with a silicone or sealant to make sure there is no space left in the tube; however, due to the halt, this could not be tested.

Figure 31: First Full System Leak Test

5.1.2. Thermodynamics Test

A thermodynamics test was set to start a few days after the project halted. It consisted of using three thermocouples positioned in locations where hot spots were expected to form: on the Xavier computer, in the lower half of the compartment where the batteries are located, and the rear aluminum end cap which is the main heat sink. An image showing the locations of the three thermocouples can be seen below in Fig. 32.

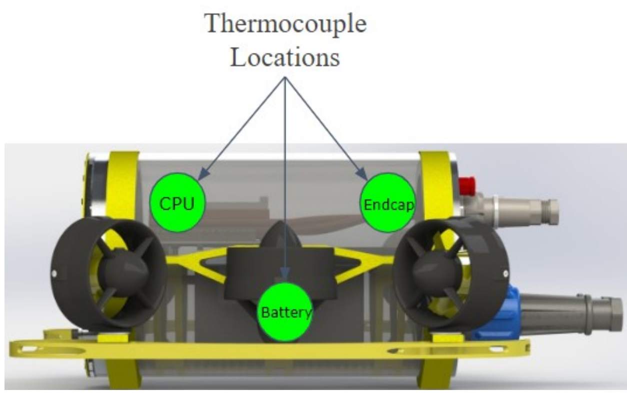

Figure 32: Electronics Tray Rendering with Thermal Straps

The AUV would then be operated in the water under heavy load for at least 10 minutes. After the 10 minutes, the data recorded by the thermocouples would be recorded. As long as the temperatures are all under 333K, then the test would be considered successful. This test would be repeated at least three times in order to simulate the mission. At the end of the test, the thermocouple data would again be examined and the thermal rejection system would be considered successful as long as the temperatures all remained under the maximum operating temperature. Furthermore, we could use the data gathered in the experiment to verify whether the predictions made by the thermodynamic model were accurate. This would correspond to the thermocouples showing an average temperature of about 306K throughout the testing period.

5.2. Electrical

5.2.1. PCB Testing

To validate requirements that the AUV shall be self powered and incorporate a kill switch, the functionality of the custom designed PCB was tested. The PCB has 5 outputs and their voltages were tested using a multimeter and hooking the PCB up to a power supply. They output the correct voltages. The second function of the PCB was the kill switch which was partially validated. It was tested with the same set up as before, hooking the PCB up to a power supply and measuring the output with a multimeter, but now dipping the leak sensor into water. When the leak sensor was activated, the power wasn't shut off completely and the voltage was only lowered due to an oversight in the design. This was due to an oversight in the design in which the cutoff switch turn off power to the cutoff switch allowing the voltage to come back. A second PCB was designed ready to be order and tested to correct this oversight and validate this requirement.

5.2.2. Power System Test

In order to validate the requirement that the AUV shall be self powered, a full power system test was conducted. The battery was used as the power supply which was connected to the PCB and voltage converters which were plugged into an artificial electronic load to simulate the electronics running during a mission. The artificial load was set to the average expected power draw of all electronics based on the power budget model, and the battery output charge was monitored during the duration of the test. The battery powered the system at very close to the desired 13 V for an hour and twenty minutes giving plenty of margin for the hour long mission, and validating the self powering requirement.

5.2.3. Software

The software sub-team conducted many tests, both in and out of the test environment, with the aid of the other two sub-teams. The most important of these are as follows:

5.2.4. Live In-water Image Processing Test

The live in water test was completed earlier in the semester. This test involved submerging the camera into the pool in an acrylic box while running a YOLACT model trained on previous data to identify various colored balls in the water and the walls of the pool. The main purpose of this test was to determine whether or not YOLACT could be run in real time on the on-board computer while identifying points of interest as desired. This test was also run with the depth camera running in real time. The image processing algorithm first identified objects and applied masks to them through YOLACT. Following this, points were randomly sampled within each mask from which depth values were extracted. The mode of the extracted depth values was then used to derive a depth estimate for each object identified. Together, this test was meant to determine that the entire image processing stack would be able to function properly in real time. This test resulted in a successful demonstration of both the point of interest identification and depth processing capabilities of the image processing system. Depth was estimated to within around 1 ft for masks identified, and the entire process was running at around 3.2 fps using the on-board computer. This test validated requirement 5.2 through showing that points of interest could be identified by the image processing system.

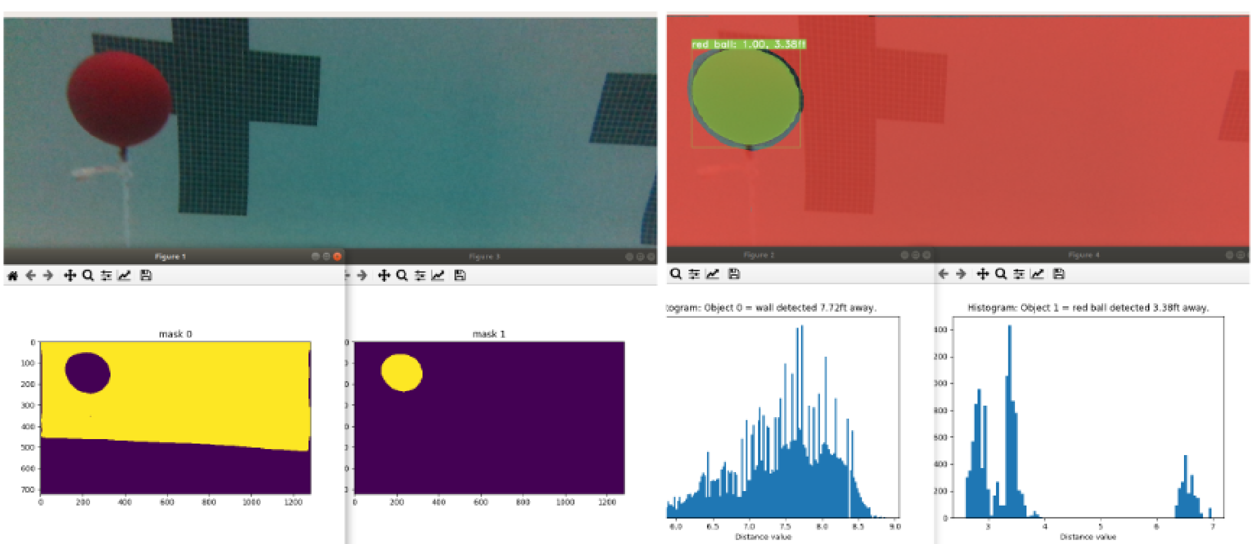

Figure 33: Example of Output From Image Processing Test

5.2.5. Simulated Controls Test

The simulated controls test was implemented in gazebo with an imported model of the YELLOW submarine. This model was placed in a pool environment simulated through walls with collision detection and a buoyancy plugin to simulate a water environment. By connecting Ardusub functionality to motors connected to the imported AUV model, the controls were able to be accurately simulated as in a real world test. The main purpose of this test was to determine the functionality of the ArduSub control suite with regards to the AUV, as well as ensure that desired control could be achieved over the AUV well before a real world test was carried out. The results of this test were a success, with the AUV responding to each control order input to ardusub in the desired way. The test script used ran every control command available in ArsuSub, including vertical, horizontal, roll, and yaw motions. These commands were verified to be producing the expected results based on visual observations of the AUV live in simulation. This test verified requirement 2.1.1, which states that the AUV shall navigate autonomously underwater. This requirement was verified through the confirmation of the AUV's desired motion in 5 degrees of freedom.

5.2.6. WiFi Transfer Test

This was a very simple test that only required the Xavier, a computer, and the team's router. Before the test began, the computer ran the setup script as discussed above. A couple hundred images were loaded onto the Xavier, which was then ordered to run the commands that would connect to the computer and send the images over. This test resulted in about 400 images being transferred in approximately 3 seconds. It also confirmed that the key was successfully installed on the computer using the setup script, as otherwise a manual password input would have been necessary. This test validated requirements 3.2 and 4.2 by showing that the images could be transferred to the ground station computer using the team's WiFi router and that the process could be completed in less than five minutes.

A sequel test was planned for the latter half of March in which the same procedure would have been followed, but with the Xavier on board the AUV on the surface of the water in the test environment. This test was expected to succeed due to the inclusion of the antenna onto the Xavier, substantially boosting its ability to connect to the router.

5.2.7. Full Stack Test

The Full stack test meant to serve as a verification of the full functionality of the control and image processing systems, as well as a confirmation of their successful integration. In this test, the image processing system would be run live in water in the real world as described in the live in-water image processing test section. The resulting masks and depth data would then be passed to the state machine. The state machine, which is responsible for all navigation and mission implementation decisions would output some control orders based on the current position and orientation of the camera within the pool. For example, if the camera were facing a point of interest such as a colored ball dead on from a distance of 5 feet away in the pool, the state machine would interpret the position and depth of the ball mask and enter the translate state of the state machine. The control output in this case would be orders for the AUV to move straight forward. The output of the state machines control decisions would be passed to Ardusub controlling a model of the AUV in gazebo, as described in the simulated controls test section. The resulting movements of the simulated AUV could then be compared to the desired movement based off of the position of the camera in the water relative to other objects. This test would verify the functionality of many aspects of the software architecture, including the image processing system, the state machine, the control system, and the integration of all these components. This test would also complete validation of requirement 2.1.1, which states that the AUV shall navigate autonomously underwater. This test was unable to be completed before the project was ended in March, due to it being scheduled for a later date, along with the integration of the image processing system with the state machine not being fully complete at the time of cancellation.

5.3. Full System

In order to ensure the AUV not only functioned as intended but full filled its intended purpose, team YELLOW Submarine designed a testing suite to verify that every subsystem of the vehicle functioned individually, then together as a system. After the system was integrated together, a period of sea trials were to have been conducted to ensure the AUV could control itself underwater, and execute its mission. During these sea trials we would formally verify each of our design requirements, while tweaking the system to eliminate any performance deficits we noticed. Following the sea trials, the AUV was to have been run through a complete demonstration mission for our Lockheed Martin project advisors and aerospace engineering faculty. This demonstration would allow the Lockheed Martin advisors of the project to confirm that the AUV performs the mission they envisioned for it, thus validating our project.

At the systems level, both of these tasks the testing would commence by placing our points of interest obstacle course around the dive well at the recreation center. Once the course is laid out and all are clear of the pool, we would continue by attaching the battery to the electronics on the shelf, and then insert the electronics shelf into the dry space volume of the AUV. Once sealed, one of our team members would activate the AUV using the rear switch, and we would verify that the lights on the boards of the AUV activate, the chimes of the motors sound to indicate they are powered, and that we are remotely communicating with the vehicle via the ground station. One of our team members would then set the AUV gently in the water. Upon verifying that the AUV has no major leaks, we would then issue the command for the AUV to begin its mission, and assume a passive roll in the test. Each time it would surface to transmit data we were to monitor the ground station and check the water content of the AUV, and if we were to have noticed at any point during the mission the AUV was in distress we would wait for it to surface, de-power it, and retrieve it. Assuming mission success our responsibility would be identical, we would retrieve the AUV upon it reaching the surface of the pool.

6. Risk Assessment and Mitigation

Samuel Kersting, Danny Liebert, Jacob Siegel, Caleb Sytner, Micah Zhang

Risk	Color
1) Object Misidentification	
2) Sealing Main Compartment	
3) Stability of AUV	
4) Compartment Temperature	
5) Camera Integration	

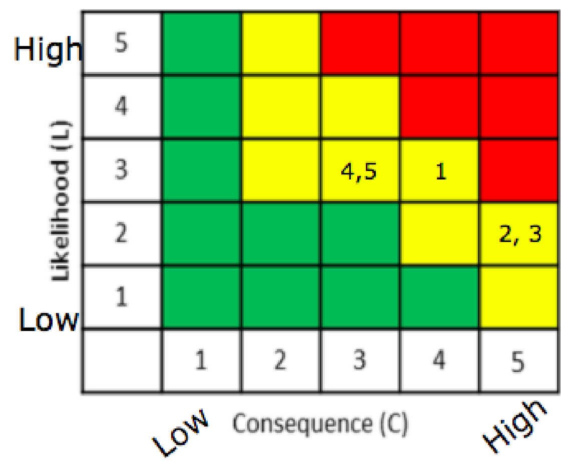

Figure 34: Project Risks Matrix and Key

The YELLOW Submarine team has found risk tracking to be a very important aspect of staying organized and delegating what work needs to be done. Tracking risks in a matrix shows the likelihood of each risk occurring and the consequence if the risk does occur. Risks with high likelihood and high consequence stand out as the most alarming and the team must work to mitigate those risks. At the beginning of the design phase of the AUV, many risks started out as high likelihood and high consequence but as the design has continued, the majority of these risks have been partially or entirely mitigated. The team still identifies 5 main risks on the project, as illustrated by Fig. 34. These risks and their targeted mitigation are further explained in the following sections.

6.1. Object Misidentification

Object misidentification occurs when the AUV incorrectly identifies something in frame as being either a POI or part of the pool wall. The primary source of misidentification in a pool environment will either be due to reflections off the surface of the water or identification of the pool floor as part of the pool wall.

This risk has a likelihood score of 3 because POI and their reflections are almost identical to one another visually. Furthermore, the pool walls and the pool floor are extremely similar visually, with very few obvious distinctions. As such, it will be a challenge for any neural network to both be able to tell POI apart from their reflections as well as to tell the pool wall apart from the pool floor.

This risk also has a high consequence score because a misidentification of the reflection of POI as the actual POI or miss identification of the pool floor as part of the pool wall could have disastrous consequences for the mission. For example, if the AUV decides to target a reflection of a POI on the surface of the water, it would result in the AUV surfacing earlier than planned. It may also become stuck in a loop where it keeps descending and resurfacing towards reflections without capturing any images of the actual POI. Furthermore, if the AUV misidentifies the pool floor as being part of the pool wall, then this will throw off the distance estimate from the AUV to the pool wall, either causing the AUV to think it is closer to the wall then it actually is (at smaller depths) farther away (at larger depths). Recall that accurate distance sensing is critical for the AUVs sense of spatial awareness. Thus, inaccurate distance estimates may cause the AUV to collide with the wall or otherwise hamper the performance of its navigation algorithm.

This risk has been mitigated since it was first listed as a red risk. The software team curated a large custom dataset with many examples of images that contain reflections of POI in many distinct scenarios as well as many examples of images that contain both the pool wall and pool floor. This enables the neural network (YOLACT) to learn the subtle differences between actual POI and their reflections as well as the subtle differences between the pool walls and the pool floor. Along with this custom dataset, the team thoroughly tested the performance of the neural network at frequent intervals leading up to the final demo. This was done by deploying a rolling approach to the collection of training data for the custom dataset. Instead of collecting all training data at one time and labeling it all in one session, instead the team broke up the data collection and labeling process into multiple smaller sessions, training and evaluating the neural network with each session. This allowed the team to detect issues with performance, experiment with different labeling techniques, as well as inform what kind of training data the team should collect moving forward to improve performance.

This risk is still considered a yellow risk because the fully assembled AUV was not tested in the pool due to the cancellation. Because of this, the team was not able to see if the neural network had enough training to function the AUV properly.

6.2. Sealing Main Compartment

For this project to be a success, it is critical that when the AUV is in the testing pool, all electronics are kept in a dry space. This dry space is the cylindrical acrylic housing that is holding all of the electronics. If water intrudes into this housing, there is a risk of the electronics getting wet and becoming damaged or broken entirely. Given the high cost of these electronics, the team cannot afford to lose these electronics. This is the reasoning behind a consequence scoring of 5. Originally, this risk was identified as a red risk, given that the housing was not constructed and testing could not be done on it yet. Since then, the team significantly tested the housing, and while leaks were present in some of the testing sessions, many of the tests did not have any leaks. The team was still in progress of including items that would guarantee that no water would intrude into the housing prior to the cancellation. Because of the amount of successful tests, this risk was decreased to a likelihood score of 2, but the consequence remained very high due to how much damage could be done of the electronics do get wet.

The team included many things into the design to mitigate the issue of water entering the housing. The first is using many different methods to seal the main compartment, using redundant O-rings and a rubber gasket to form a water-tight seal to the front and end caps of the housing. On the rear endcap, all components penetrating the endcap have sealing devices. The three bulkhead connectors use gaskets, and the bolts to hold the electronics tray, the three way switch, the pressure sensor, and pressure release valve all have accompanying o-rings to seal those holes. Next, all electronics are held in the top half of the housing, keeping them above where water would accumulate in the housing. Also, the design includes three leak sensors, two at the front and back of the housing sitting on the bottom and one sitting slightly higher in the housing in the middle. If one of the leak sensors near the end caps detects water, the vertical thrusters will fire bringing the AUV to the surface of the pool. If the last leak sensor detects water, this means that there is a significant amount of water in the housing so all power will be cut from the AUV to limit the damage done to the electronics. In case there is water at the bottom of the housing, there is an interior baffling to limit the amount of water splashing around while the AUV is moving. Finally, the housing is equipped with desiccant bags to prevent condensation in the housing.

The team conducted many tests to reduce the likelihood of this risk. These tests are further explained in Section 5.1.1.

6.3. Stability of AUV

Given that there are no motors to control the pitch of the AUV, it must be statically and dynamically stable in pitch. This risk comes from the AUV unexpectedly pitching while the thrusters are firing or pitching from a current in the testing pool.

A model was created to determine the static and dynamic pitch stability. This model is shown in Section 3.3.1. The conclusion of the model is that the AUV is statically stable due to the CB being above the CG. It also found that the amplitude of pitch oscillations decreased with time, meaning that the AUV is dynamically stable. Furthermore, it was found that if there is a disturbance in pitch, it will have a minimal effect on the camera's ability to track objects of interest. This risk was originally labeled as a high risk, but after creating these models, the likelihood of this risk was decreased. The consequence is still labeled at 5 because if the AUV is not stable, it would not be able to move underwater properly. This risk has not been fully mitigated because the fully assembled AUV was not successfully tested prior to the project cancellation.

6.4. Compartment Temperature

With all of the electronics being held in the waterproof internal compartment, heat is going to be produced which will increase the temperature inside of the compartment. Because all of the components inside of the compartment have a maximum operating temperature, the temperature inside the compartment is a risk to the project.

To mitigate this risk, a thermal model was created and is shown in Section 3.3.1. This model confirms that through the AUV's mission, the temperature will not get higher than 306K which is 27K below the maximum operating temperature for the battery, the constraining component. Further mitigation includes using a thermally conductive material that is connected to the back plate to transfer some heat out of the internal compartment. Attached to that will be heat pipes or copper cabling running from a copper housing around the Xavier and from the battery.

The team was unable to fully assemble the AUV due to the cancellation so the thermal test was not conducted. Because of this, the likelihood cannot be reduced further until the testing was completed.

6.5. Camera Integration

There is a risk that the Nvidia Xavier will not be able to read images from the Intel RealSense D435 Camera. The Xavier runs an ARM-based chip, and Intel devices rarely have ARM drivers. The D435 happens to have an ARM driver, but only if the chip is running Ubuntu 16.04, and even then, the driver appears to be very finicky. This is why the team gives this risk the likelihood score of 3. The combination of Xavier + D435 is very common in robotics research, so the team will be able to resolve this integration problem, but it will be a massive time sink. This is why the consequence score is a middling 3.

The likelihood of this risk has been reduced from when it started to be tracked. The team did a lot of research and testing to mitigate this risk, but since the AUV was not fully tested, this risk could not be further reduced. The consequence of this risk would have further been reduced by conducting more research on the combination of the Xavier and D435.

7. Project Planning

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7.1. Organizational Chart

The organizational chart begins with the customer, Lockheed Martin, on the top right of the chart. The customer team provided the YELLOW Submarine team with the requirements for the project. They are also constantly providing mentoring and tips throughout the designing process. The organizational chart of the YELLOW Submarine team is split up into four categories: management, mechanical, hardware, and software. The management team consists of the Project Manager, the Systems Engineer, and the Chief Financial Officer (CFO). Each member in the management team also is associated with a technical role for each sub-team. The chart then flows into each sub-team. Each sub-team has a lead along with two additional members with critical technical roles. The organizational chart is shown in Fig. 35. This particular organizational structure was chosen due to the nature of the project being multidisciplinary. An AUV has mechanical, software, and hardware/electronics components. We wanted to make sure at each of these key aspects of the project were adequately covered. Furthermore, the formation of these particular sub-teams lends itself well to the different specializations of each person present in the team. Finally, having equally sized sub-teams each with a sub-team lead allows for a high degree of management and operational efficiency.

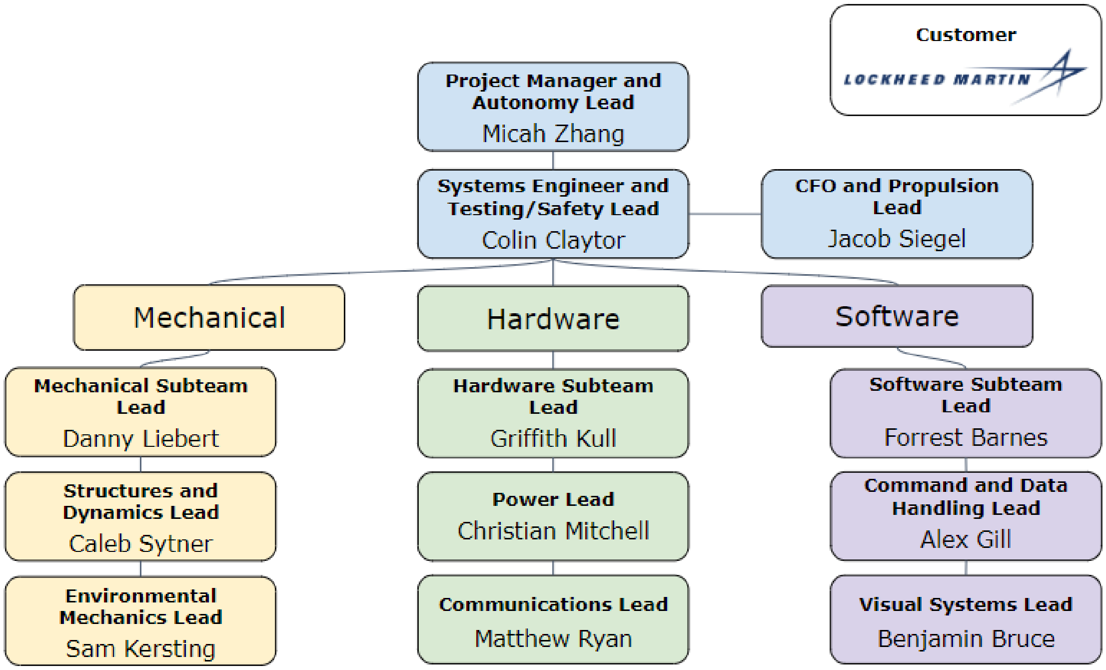

Figure 35: Organizational Chart

7.2. Work Breakdown Structure

The work breakdown structure shown in Fig. 36 displays the critical pieces of work that have been completed, were in progress, or were planned to be completed at the cancellation of the project. The current progress of each item is shown by the color of the box which corresponds to the legend in the top right corner of Fig. 36. The WBS splits into the mechanical, hardware, and software sub-teams. The two main points of work for the mechanical team is the modeling and testing of the structure of the AUV and the construction of the AUV. Models were constructed for the thermals, structure, and controls. These models were supposed to be validated through testing in the Spring semester. The team was able to complete testing for the structure, controls, and pressure, but were not able to test the thermals and all materials. The mechanical team constructed the CAD model of the AUV and a box made of acrylic was constructed to hold the camera and keep it dry while being submerged into a pool during testing. Everything was constructed except for all of the interior structure, which was in the process of being completed prior to the cancellation. The main work points of the hardware team is also modeling and testing and the assembly of all electronic components. The power, battery, and tray layout were successfully designed and tested and the team was in the process of assembling the PCB, electronics tray, and wiring. The electronics team were planning to test the temperature and pressure sensors and the kill switch. Finally, the software team was tasked with the work of developing the control system and the image processing and then integrating these two developments together. The software team completed all tasks under the control system and image processing development. Just before halting all work, the software team was in the integration phase, integrating the control system and image processing together.

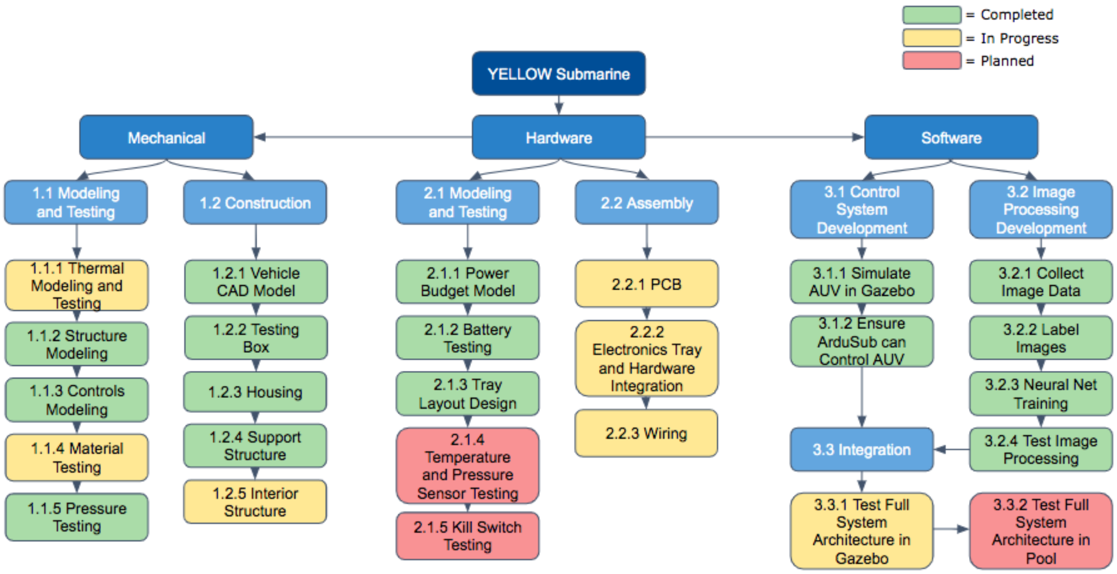

Figure 36: Work Breakdown Structure

7.3. Work Plan

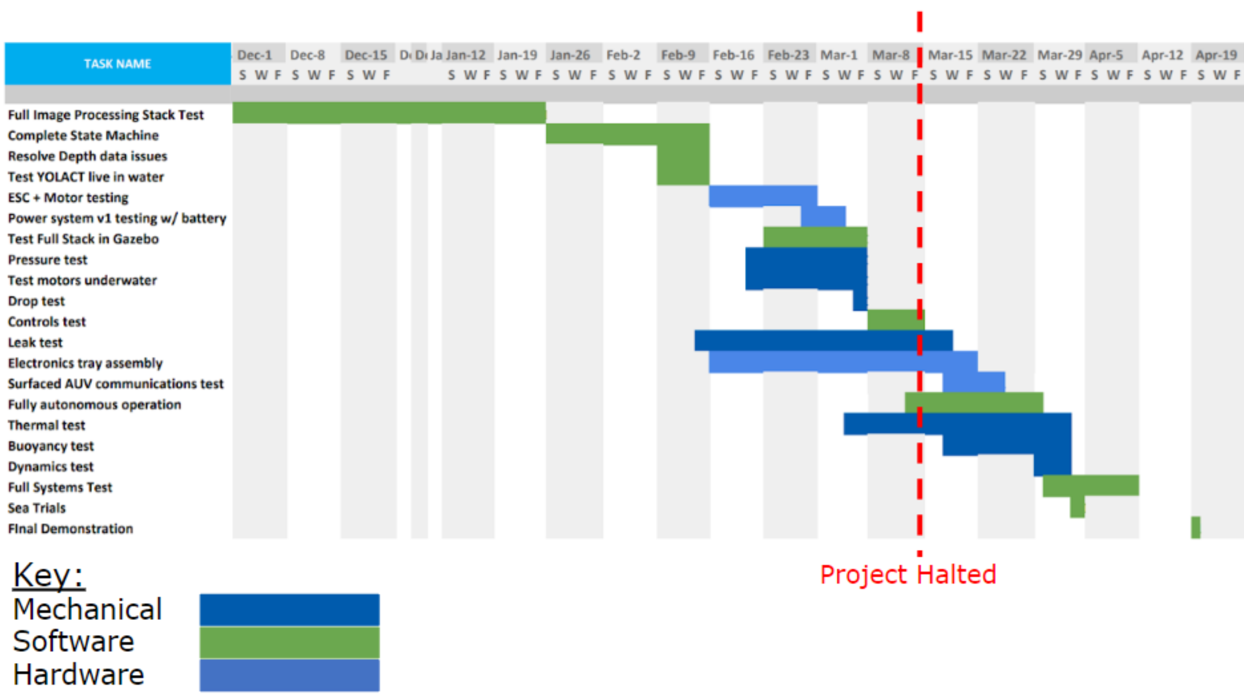

Figure 37: Work Plan by Subteam Breakdown

Figure 37 shows the critical path of the project for spring semester in GANTT chart form. It is color-coded to show sub-team breakdown. A red dotted line has been provided to illustrate the when and where the order to halt the project occurred during the development cycle. This GANNT chart was created by taking the main milestones from each individual subteam GANTT chart (see Appendix) and combining them into one chart, hence why it is our critical path. At the time of project cessation, the majority of software development had been complete. Large percentages of mechanical and electrical development were complete as well. The remaining milestones mostly consisted of systems integration tests as well as the planned final demo.

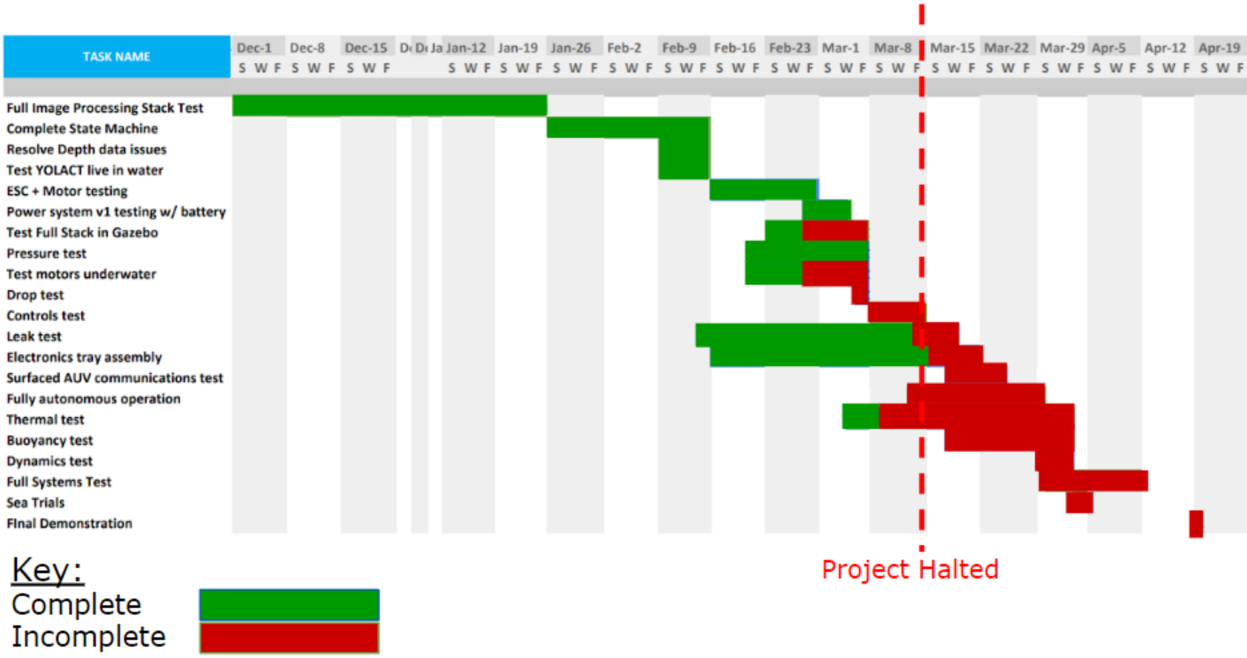

Figure 38: Work Plan by Completion Status

Figure 38 shows the same critical path of the project for spring semester, this time color-coded to show the level of completion for each milestone. As shown the chart, at the time of cessation, the team had began to fall behind on some of the milestones, mostly due to delays that had occurred at the beginning of the semester. That being said, a large amount of progress had been made in the short amount of time right before the first systems test that put the team back on track to meet the existing deadlines. Not only was the team able to fully assemble both the internals and externals of the AUV, but significant progress on software development had been made as well.

7.4. Cost Plan

At the start of the project, the team was allocated a budget of $5,000 to complete the project. Early in the Fall semester, the budget was a major constraint to the project but through research and development, the team has developed a model that will cost a total of $3,767.53. This cost left a margin of 24.65% in the $5,000 project budget which is $1,232.47. However, this cost was for parts that were not going to produce the metrics the AUV needed to be entirely successful. The team immediately searched for resources for additional funding. Towards the end of December, the team was granted $1,202.36 from the Engineering Excellence Fund (EEF) after submitting a funding proposal and giving a presentation to the board of the EEF. This additional funding provided the team with a budget of §6,202.36 and allowed the team to upgrade many parts for the AUV.

Prior to the notification of additional funding, the team planned to use a NVIDIA Jetson TX2 as the computer inside the water-tight compartment and an older model of BlueRobotics thrusters that are less efficient were being used for the vertical thrusters. The team decided to use this funding to upgrade these important components. The Jetson TX2 was upgraded to an Xavier and the thrusters were upgraded to the new thrusters, the same ones that were used for the horizontal thrusters. The upgraded computer provided a higher frames per second in the image processing which the team found was needed. Also, with the additional funding, the mechanical team was given the freedom to test many different sealing devices for the water-tight compartment, along with the ability to add some human engineering aspects to the AUV, making it easier to open the compartment.

With the upgrades to components and additional items that were purchased, the team spent $5,074.57, leaving a margin of $1,127.79 just before the cancellation of the project. The team was still planning to spend more on testing equipment and other miscellaneous items, but this did not happen because of the cancellation. Table 39 and Figure 39 show how much was spent on the major aspects of the project.

Table 39: Bill of Materials Overview

Project Element	Cost	Percentage of Budget
Battery	$227.68	3.67%
PCB	$275.00	4.43%
Thrusters and ESCs	$1,152.36	18.58%
Mechanical Structure	$1,397.30	22.53%
Sensors	$386.10	6.23%
Microcontrollers	$996.60	16.07%
Testing Equipment	$110.00	1.77%
Misc. Hardware Equipment	$329.53	5.31%
Pilot Supplies Deposit	$200.00	3.22%
Total	**$5,074.57**	**81.82%**
Margin	**$1,127.79**	**18.18%**

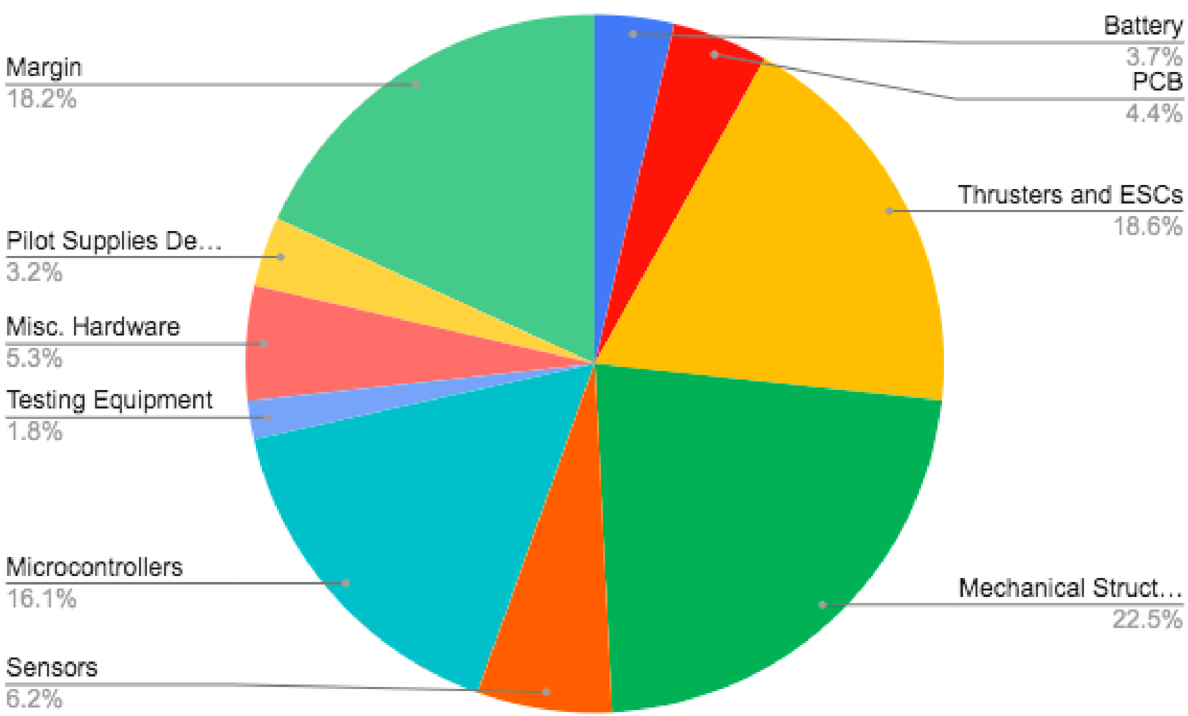

Figure 39: Project Cost Pie Chart

7.5. Test Plan

In order to fully verify our requirements and validate the system architecture of the AUV, we prepared a suite of critical tests. Minor tests occurred at the behest of each subteam between these large tests, but these official "milestone" tests were set in place as the definitive markers of project progress.

7.5.1. Full Software Simulation Test

This test was completed on February 13, 2020, and was meant to give the team a preliminary understanding of the way in which the AUV would move underwater as control inputs were given to it. We used the open source ArduSub control software as well as the Gazebo simulation environment, which is also open source.

7.5.2. Live YOLACT and Xavier Integration Test

This test was completed on February 15, 2020, and demonstrated that the team had successfully integrated the NVIDIA Jetson Xavier with the depth camera and the full image processing stack. This test successfully verified the capability of the AUV to identify points of interest, label them, and calculate the distance to them in real time. It was conducted in the Recreation Center dive well, which we secured use of by testing concurrently with RoboSub. We used buoys, ropes, and weights to create the points of interest. The Xavier, Camera, a monitor, a mouse, a keyboard, and a ”periscope” camera enclosure made up the rest of the test setup. The monitor, mouse, and keyboard were all provided by a team member, while the ”periscope” enclosure was manufactured by our Mechanical sub-team.

7.5.3. Leak Test

This test was conducted on February 21, 2020, and was meant to demonstrate that the dry volume of the AUV meant to house the electronics was indeed watertight. We used the diving well at the Recreation Center on campus to conduct this test. Due to some a communication error between the team and the managers of the Rec Center, we did not have a formal reservation of this pool, but a lifeguard allowed us to conduct this test while the pool was unreserved. The hardware used in this test includes the AUV structure, butcher paper, tape, lengths of nylon rope, and some weights.

7.5.4. Full Power System Test

The Power System was tested on March 5, 2020 in the aerospace building electronics lab to confirm it worked as intended for the impending controls system test. This test used the power system, electronic load, and a multi-meter. Facilities and equipment was provided by the aerospace department upon completion of an orientation.

7.5.5. Six Motor Bench Test

This test was conducted on March 4, 2020 in the aerospace electronics lab, and was designed to test the control responses of the AUV motors prior to the Dynamics/Controls Test. We used an external power supply to provide power to the motors, the NVIDIA Jetson Nano, a monitor, a mouse, a keyboard, the PixHawk, the ESCs, and the Motors to conduct this test. The power supply, monitor, mouse, and keyboard were in the electronics lab, which we gained access to through an orientation. The Nano was procured specifically for testing.

7.5.6. Dynamics/Controls Test

This was the final test the team conducted, albeit unsuccessfully since we encountered electrical problems from hasty final assembly we had no way of fixing. It was conducted on March 14, 2020, prior to the order to cease working, and intended to demonstrate the AUV’s ability to move through the water and submerge under its own power. We used a partially integrated AUV system (missing science equipment, camera, using the Jetson Nano instead of the Jetson Xavier) as well as the personal laptop of one of our team members to conduct this test. The pool we used was one of the few still open in Boulder, at the Sterling University Peaks apartment complex. We gained access to the pool due to the goodwill of a friend, Cavan Roe.

7.5.7. Drop Test and Leak Test 2

These tests were scheduled to be completed on March 8, 2020, but were postponed what ended up being indefinitely due to the full team push to complete the controls test prior to project suspension. It was intended to verify the drop requirement of our project and serve as proof that the fixes made following leak test 1 were successful. We would have used the Rec Center diving well for these tests, and were in the process of reserving them. The hardware would be the integrated AUV structure with mass analogs inside, butcher paper, nylon rope, and weights.

7.5.8. Thermal Test

The Thermal Test was to occur April 2, 2020, and was intended to verify that the AUV’s internal steady state temperature was within operational limits. We would have reserved time in the Rec Center Dive Well for this test. We would have required the mostly-integrated AUV, nylon rope, weights, thermocouples, and one of our laptops to read the data off of the AUV.

7.5.9. Sea Trials

This test was intended to be conducted on April 5, 2020, and would have served as an opportunity for the team to verify requirements and debug the system. We planned to conduct this test at the Gold Run apartment complex pool, and were in talks with a friend of the project living in the complex to open up the pool to us. The test would have used the fully integrated AUV and a laptop to talk to it for the system hardware. The points of interest in the pool would have been made with buoys, nylon rope, and weights.

7.5.10. Demonstration

This test was scheduled for April 19, 2020, and would have served to validate our AUV's capabilities with our Lockheed Martin project sponsors. We were planning on conducting the test in the Recreation Center dive well, which we in the process of reserving for a two hour window on the weekend of April 18-19. We would have used the nylon rope, weights, and buoys to lay out the obstacle course. The AUV and one of our laptops would have been the only other components of this test.

8. Lessons Learned

Micah Zhang, Benjamin Bruce

The biggest lesson learned by the team came as a result of the sub-team structure adopted at the beginning of the project. The sub-team structure carried a lot of successes with it, but it had one large drawback that was not anticipated. All of the project scheduling happened on a sub-team basis using the class deliverables as guidelines. As a result, each sub-team had its own schedule that it tried to keep to. This worked well until integration began, at which point the team realized that the three schedules could not work together due to each milestone relying on one from other teams. For example, the software sub-team planned on testing the controls in the second half of March, but the mechanical team had not planned on assembling the AUV until the very end of that month. The result was that all of the schedules needed to be reworked, which could have been avoided if the sub-teams had been talking to each other about it when creating the schedule originally. This leads to the largest piece of advice for future teams.

The YELLOW team would advise any future senior projects teams that have a similar sub-system breakdown to allow for communication between each sub-system as soon as something happens or is decided that affects another team. Using the example above, the integration schedule is something that affects all three sub-teams, and so it was something that should have been discussed when the scheduling decisions were first being made, rather than only days or weeks before it matters.

Another important lesson learned, or rather, reaffirmed, was the importance of open, transparent communication within the team. When using virtual team communication applications, such as Slack, in general, try to keep all messages within the group channels and stay away from using direct messages. This allows multiple people to weigh in on new ideas, clarify areas of confusion, as well as help make key decisions. Furthermore, try to establish project expectations early in the semester. This, combined with open communication reduce the chances for surprises to occur and ensures optimal group operation. In addition, when it comes to assigning project roles and determining team structure, the sooner this is completed the better. This reduces uncertainty and helps expedite the trust building process within the team. Finally, it is highly advised the future teams stick with a hierarchical org-chart that incorporates semi-autonomous sub-teams. A hierarchical sub-team structure lends itself well to efficiency as does semi-autonomous sub-teams. The assignment of sub-team leads that are the subject matter experts for their subsystem greatly lessens the risks of mismanagement and allows for smooth, lean operation.

9. Individual Contributions

Forrest Barnes

System Architecture - Software, Design - Software - Control System, Design - Software - State Machine, Design - Software - Ground Station, Continuation - Software

Benjamin Bruce

Conducted the localization trade study, requirements development, ground station design and creation, image labeling, pool testing, and wrote for the software sections(design, manufacturing, and V&V), the requirements section, and the lessons learned section

Colin Claytor

wrote functional requirements section, compiled trade study subsection, wrote design requirement subsection, compiled system architecture subsection, wrote full system verification and validation subsection, wrote test plan subsection

Alexander Gill

Control system, Simulated Controls test, full stack test, live in-water image processing test

Samuel Kersting

Verification and Validation - Leak and Thermodynamics Tests, Risk Assessment and Mitigation - Compartment Temperature

Griffith Kull

Project Objectives and Functional Requirements Section- CONOPS, Functional Requirements Subsection, System Architecture- Electrical Subsection, Verification and Validation- PCB Testing and Power System Test Subsections

Danny Liebert

Mechanical Manufacturing, Sealing main Compartment, Mechanical Manufacturing Continuation, CAD drawings and images

Christian Mitchell

Power system trades, PCB design and testing, power system testing, power budget, interconnect diagram.

Matthew Ryan

Trade Studies - Electronics and Hardware, Design Requirements tables and some subsections, Manufacturing - Electrical, Formatting and minor edits

Jacob Siegel

Trade Studies - Mechanical, Risk Assessment and Mitigation, Project Planning - Organizational Chart, Work Breakdown Structure, Cost Plan

Caleb Sytner

System Architecture - Mechanical, Continuations: Mechanical Testing, Risk Assessment and Mitigation: Stability of AUV, stability model development, impact force model development, beam bending model development, dynamics test procedure, drop test procedure

Micah Zhang

Project Purpose, Project Objectives, Trade Studies, System Architecture - Software, Manufacturing - Software, Verification and Validation - Software, Risk Assessment and Mitigation - Object Misidentification, Project Planning, Lessons Learned

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Appendix

9.1. Continuations

Forrest Barnes, Danny Liebert, Caleb Sytner

9.1.1. Mechanical Testing

Requirement 5.3 mandates that the AUV must be able to withstand an impact to the surface of the water from a drop height of 2.5 ft. To verify this requirement, the drop test was created. The diagram for the drop test can be seen below.

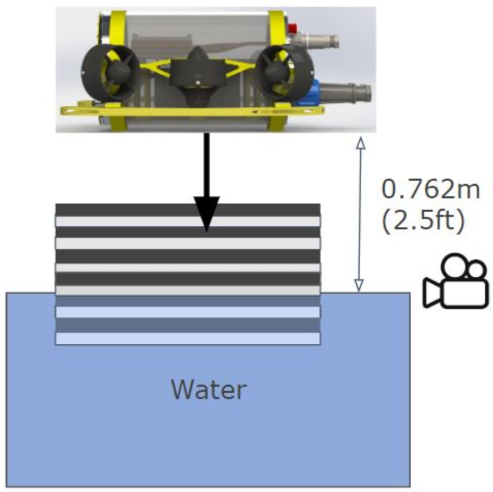

Figure 40: Drop Test Diagram

The test starts with lining the inside of the acrylic tube with paper. This paper will make it easy to identify if any water breached the dry space. The electronics tray will then be loaded with weight to simulate the weight of the full AUV since none of the electronics will be in the AUV for the test. A distance reference board will then be placed behind the impact site and a camera will begin filming. Following this, the AUV will be dropped from a height of 2.5 ft above the water and retrieved. The structure will then be inspected for damage and the paper will be inspected for wet spots. The test will be considered a success if the structure shows no signs of damage or warping and the paper has no wet spots. Following the test, the camera footage in conjunction with the distance reference board will show the impact velocity and allow the team to estimate impact time. These values can then be used in the impulse momentum theorem equation to validate the impact force model. Since all of the assumptions used in the derivation of the impact force model increase the predicted impact force, it was expected that the actual impact force would be less than that predicted by the model. As a result, the team expected the AUV to withstand the impact caused by the drop with no structural damage or water breaches.

Due to the AUV not having active control in pitch, there was some concern about the stability of the AUV. To address this, a stability model was created and a test plan was drafted. The diagram for this test is shown below.

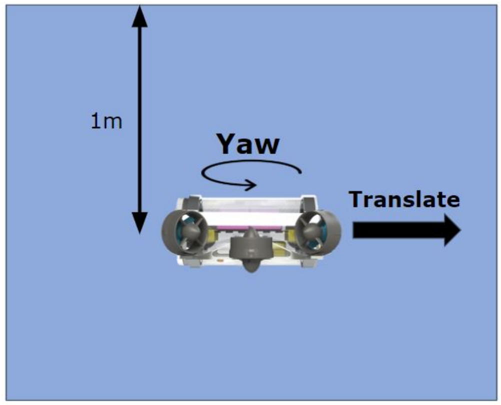

Figure 41: Dynamics Test Diagram

The first step in the dynamics test is to start filming with a GoPro, place the AUV into the water, and command it to descend to a depth of 1 m. At this depth, the AUV will be manually disturbed to test its static stability. If the AUV displays static stability, it will be commanded to yaw in place to observe its dynamic stability under rotational motions. The AUV will then be commanded to translate forward for 15 seconds to observe its dynamic stability under translational motion. After the test, the IMU measurements onboard the Pixhawk will be plotted to validate the dynamics model, and in the event these measurements were unusable, the camera footage could be used as a backup to estimate pitch angles at a given time to validate the model. The team expected to see dynamics behavior that, while stable, did not match those predicted by the model. This is because the CG of the AUV would likely not be in the same place as was predicted by SolidWorks and used in the model. To account for this, the lead weights inside the AUV could be moved to change the location of the CG closer to the predicted location.

9.1.2. Mechanical Manufacturing

As mentioned earlier because the project was halted well before completion, there are still several parts were still left to be manufactured. Nearly all of the exterior components were manufactured except one small part. This was the spacers for the endcap clips. These are used as shoulers around the bolts so that the clips are parallel with the endcaps. These are very simple parts as they only need to be cut to length as shown in Fig 51 for the front, and Fig 50 for the rear.

The D435 visual depth camera is attached to the electronics with a custom mount. This serves a couple purposes as it was found that the camera would get significantly hot when test, therefore the mount acts as a heat sick to transfer heat to the electronics tray and out the endcap. The original design incorporated fins to help dissipate heat but as that would just increase the internal environment temperature, they were removed and the design simplified. The camera mount can be seen in Fig 52. This requires two sets of holes to be drilled, one of has a 1/4-20 thread to attach to the electronics tray. The other set has a larger relief to allow an M3 bolt head to sit behind on a flat surface.

Because the electronics tray is partially acting as a thermal transfer system to the endcap, it is important that the tray has a solid contact point with the endcap to promote better conduction. This is achieved from the custom mount that connects the electronics tray to the rear endcap. This part is shown below in Fig 53. This part is complex in that there are quite a lot of holes to be drilled and milled that need to roughly line up from top to bottom. The four holes going through the back are meant for M5 sealing bolts to attach to the endcap. These holes also have half inch reliefs cut in to ensure there is enough clearance for a nut on the inside. The three vertical sets of holes are for attaching the electronics tray, which is intended to slide into the slot. Again, the holes have reliefs to provide a flat and give enough room for the M3 bolt heads and nuts. The slot was intended to be cut using a slitting saw, and the slot was also intended to be used with thermal paste to maximize the heat transfer from the electronics tray to the encap. This should conclude the aluminum manufacturing.

Because the thermal concerns on the interior of the AUV, the team designed a heat transfer system for the xavier as this was assumed to be the hottest component. This system is comprised of a copper housing around the heat sink of the computer, heat pipes to transfer the heat rearward, and a thermal block connected to the rear endcap. The copper housing was intended to be manufactured with four pieces of 1/16 in. copper sheet. These would be braised together to form a box sized to fit tightly around the aluminum heat sink of the xavier. From there heat pipes where planed to be used to transfer the heat from the xavier to the endcap. However, the team was unsure of the bending capabilities of the heat pipes, so large gauge copper cables were ordered as well as a back up. These would also be braised or soldered to the sides of the copper sheets. Finally, bolted to the endcap or attached with thermal adhesive, a collection block was to be manufactured to transfer the heat from the heat pipes to the emdcap. As this design was implemented late in the process, there are no formal drawings of the parts, however they can be seen in the CAD renderings below.

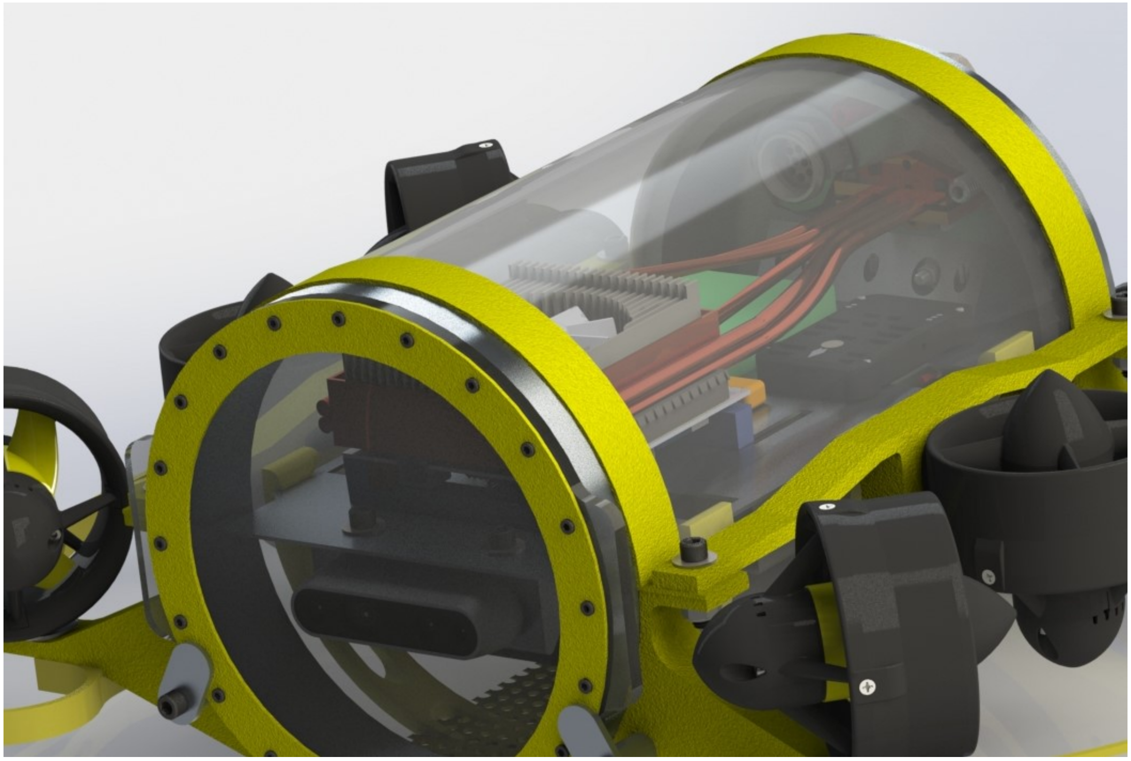

Figure 42: Heat Transfer System

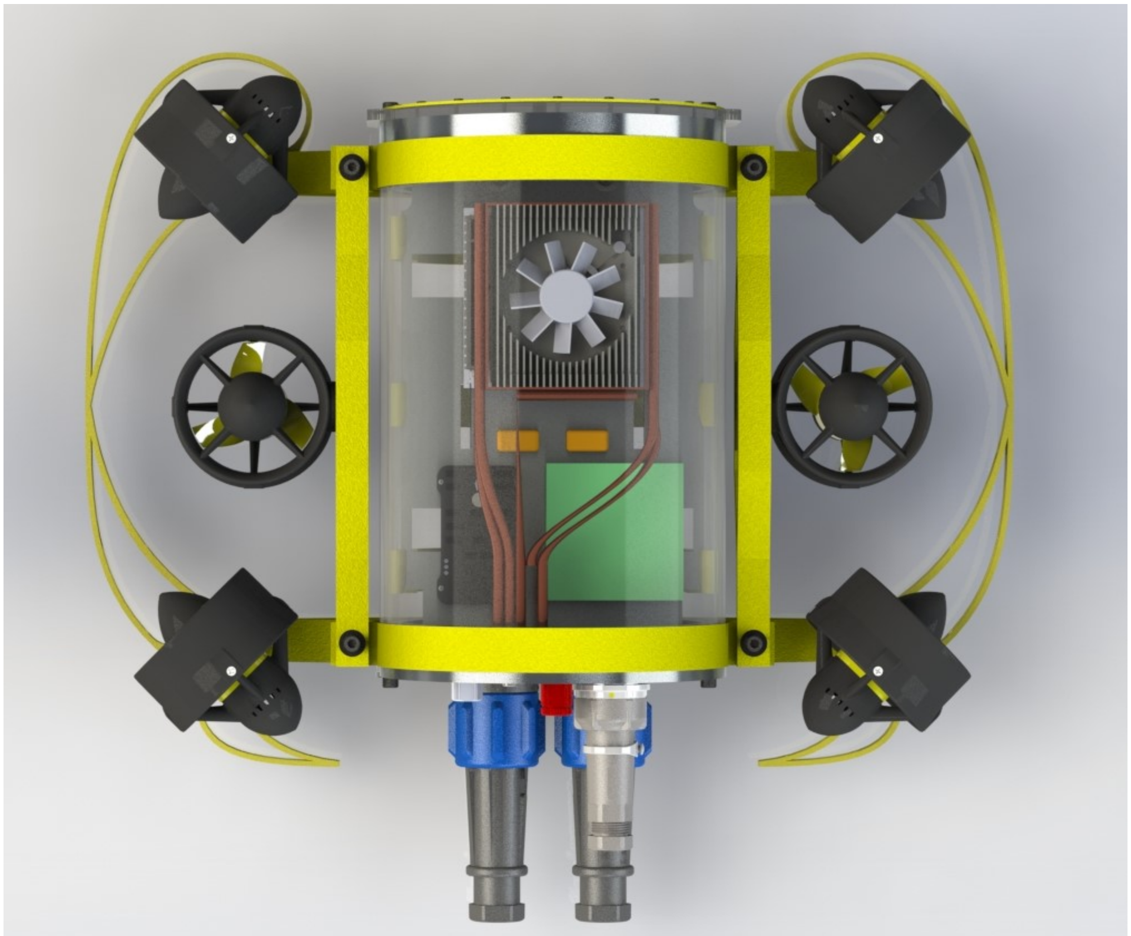

Figure 43: Heat Transfer system Top View

The last set of parts that was still to be manufactured were the bumpers. After iterating through a few designs of the bumpers, the team was only able to 3D print a completed final set of front and rear bumpers.

Additionally the team found that removing the rear endcap with o-rings in place was extremely difficult. To aid in the human factors of this, handles had been purchased to better pull the endcap off. However, these were not able to be integrated before the project was stopped.

Finally, the team intended on powder coating the exterior aluminum component yellow in resemblance of the team name. This was unfortunately not able to be completed before the project was stopped.

9.1.3. Software

The biggest software task for any future team picking up this project will be integrating the pieces that have already been developed. YOLACT must be integrated with the state machine. One must modify the state machine code to create a new thread that does nothing but call YOLACT, pass images to it, and return masks from it. This will ensure YOLACT is never kept waiting. Just keep passing it images. The main thread must then take the masks and integrate them with the depth images to create the distances to each object. Everything after that is mostly done, but needs testing.

The second software task the future team must complete is the simulation. I STRONGLY RECOMMEND AGAINST USING GAZEBO. Develop your own simulation using the Unreal engine. Start by figuring out how to make water work in Unreal. You can use a neutrally- or slightly-positively-buoyant ball to test this. Then take the SolidWorks model of the AUV and put it into Unreal. It took about a week to figure out how to do this in Gazebo, but I've heard that it is almost click-and-drag easy in Unreal. Then one must add the motors to the model. I believe most difficult task for this future simulation will be the next one: figuring out how to connect ArduSub with the simulation. This will probably be an Unreal engine plugin module, with the interface to ArduSub modeled after the ArduSub Gazebo plugin. The final step is what really tripped us up in Gazebo, but should be trivial in Unreal: get the output from the camera and send it to the state machine code. You may need to develop a second plugin to get depth image data, but I think that will be a relatively simple matter.

This seems like a lot of work for a simulation, but towards the end of your project you will thank me. Code that hasn't been tested is universally wrong, and this simulation will be the only way to test your code on a day-to-day basis. I can't imagine trying to write some bit of code and only learning a week later whether it worked or not. I wouldn't be able to develop at all. Live tests are expensive, simulation tests are cheap (once you have the simulation running). Also, Unreal engine is hecking pretty. We wowed the PAB on every single presentation with our simulation gifs, and yours will be even better.

Part Drawings

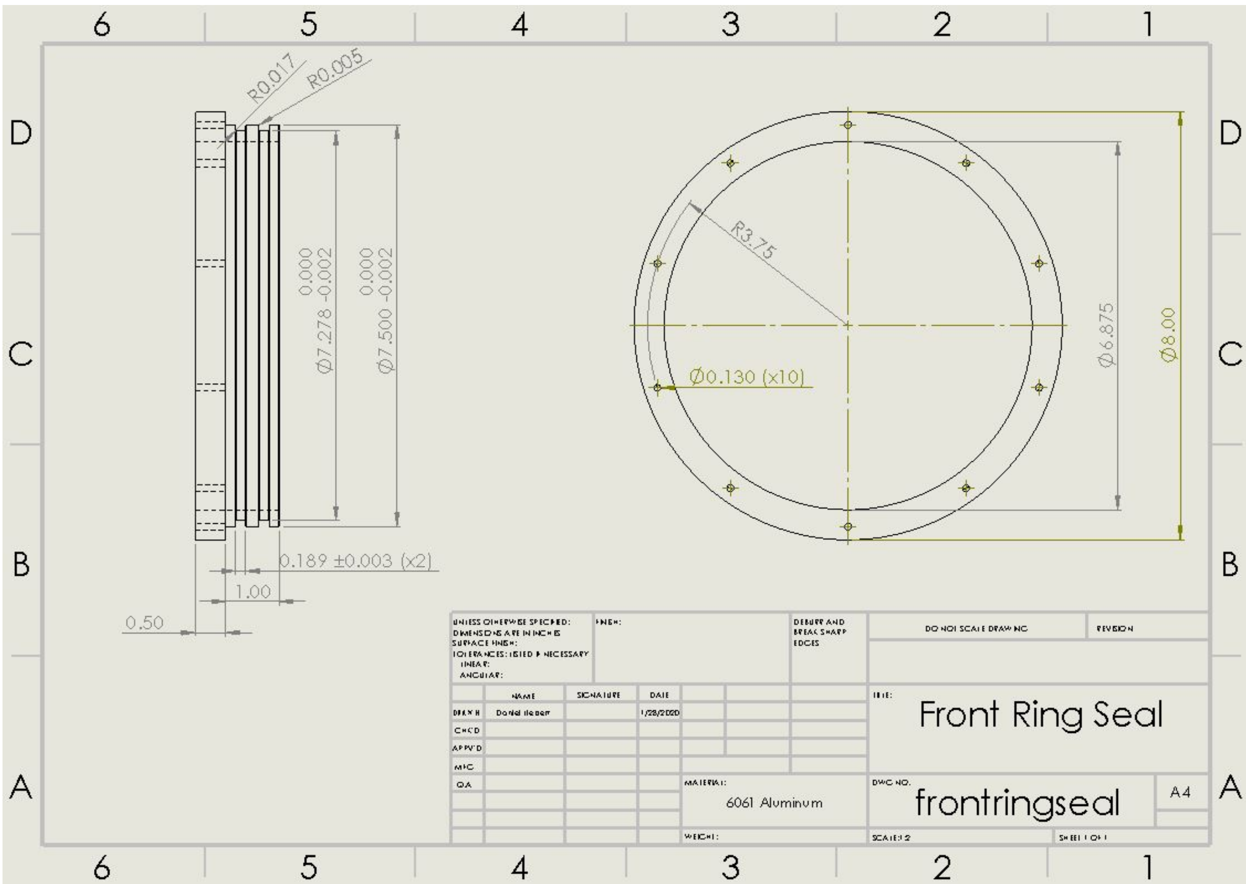

Figure 44: Front Ring Seal Drawing

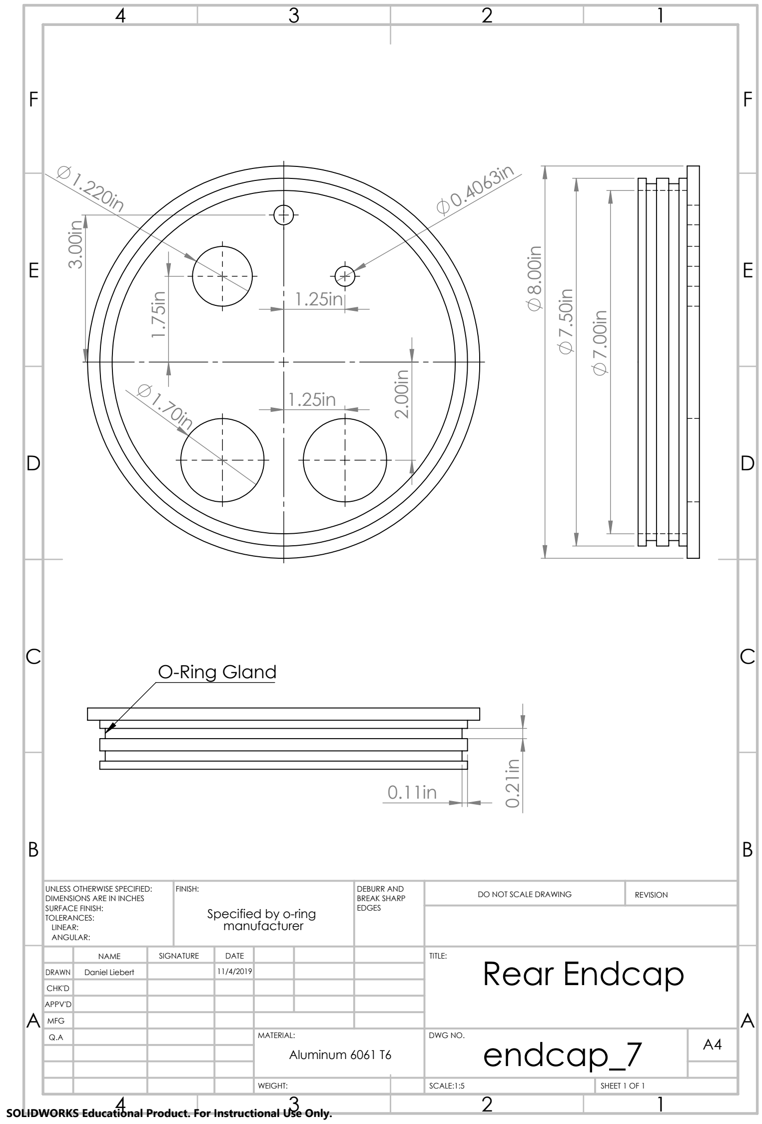

Figure 45: Rear Endcap Drawing

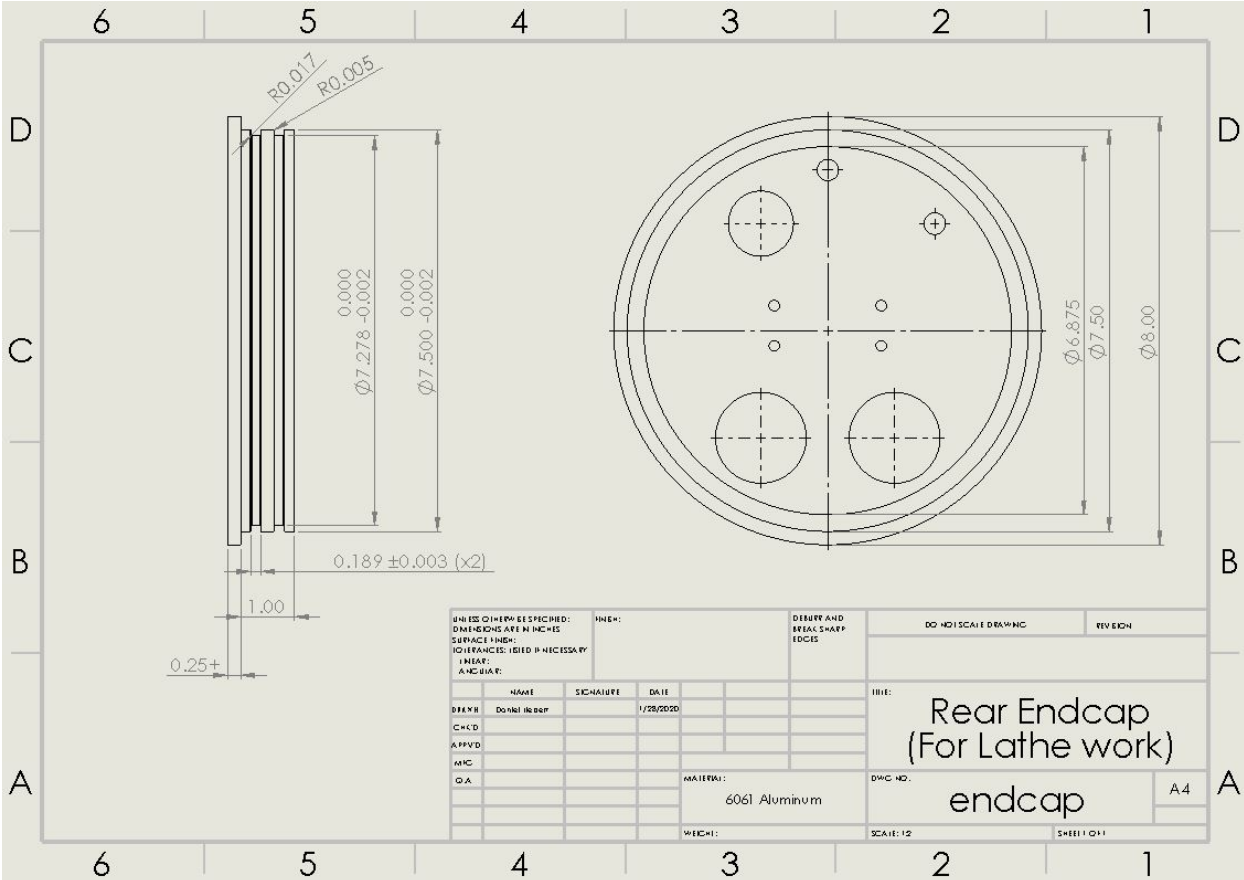

Figure 46: Rear Endcap Drawing 2

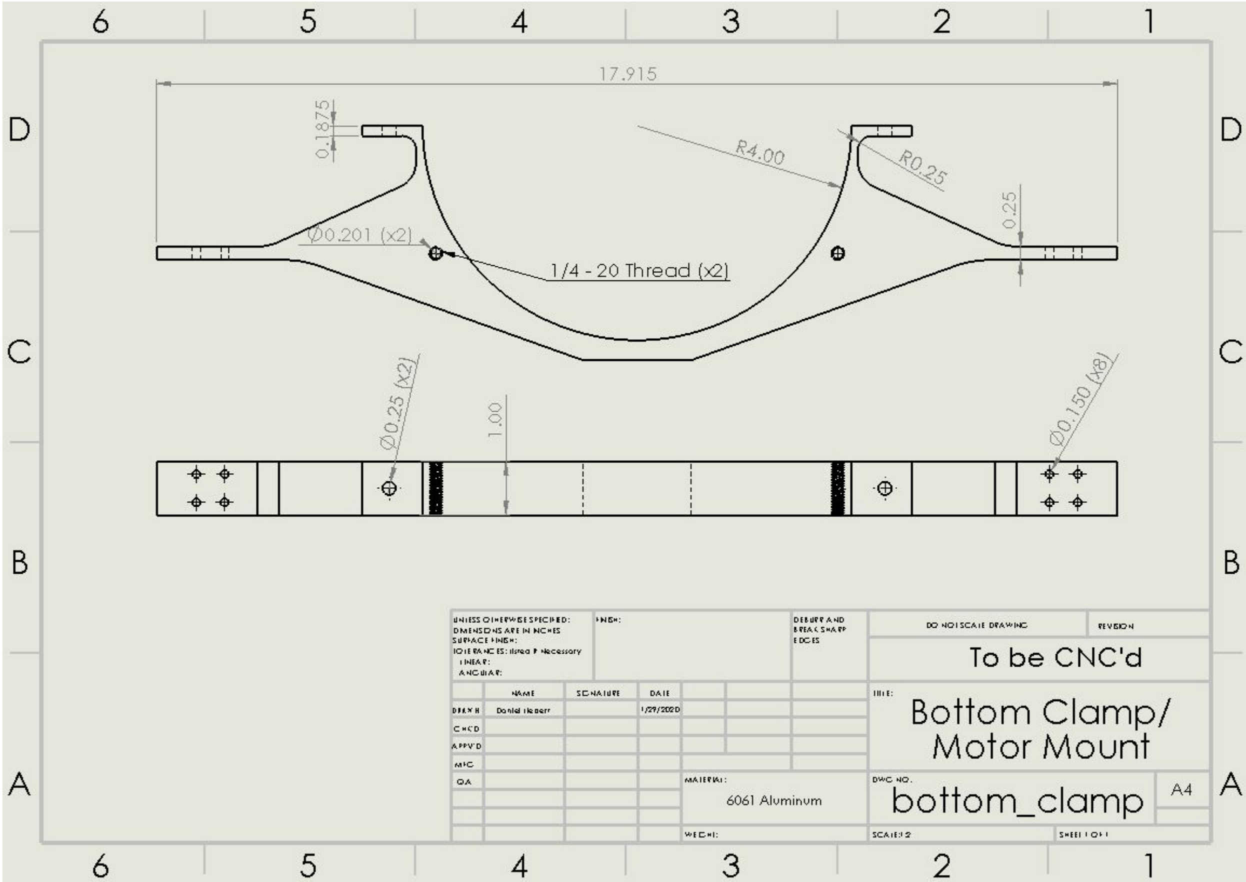

Figure 47: Bottom Clamp/Horizontal Motor Mount Drawing

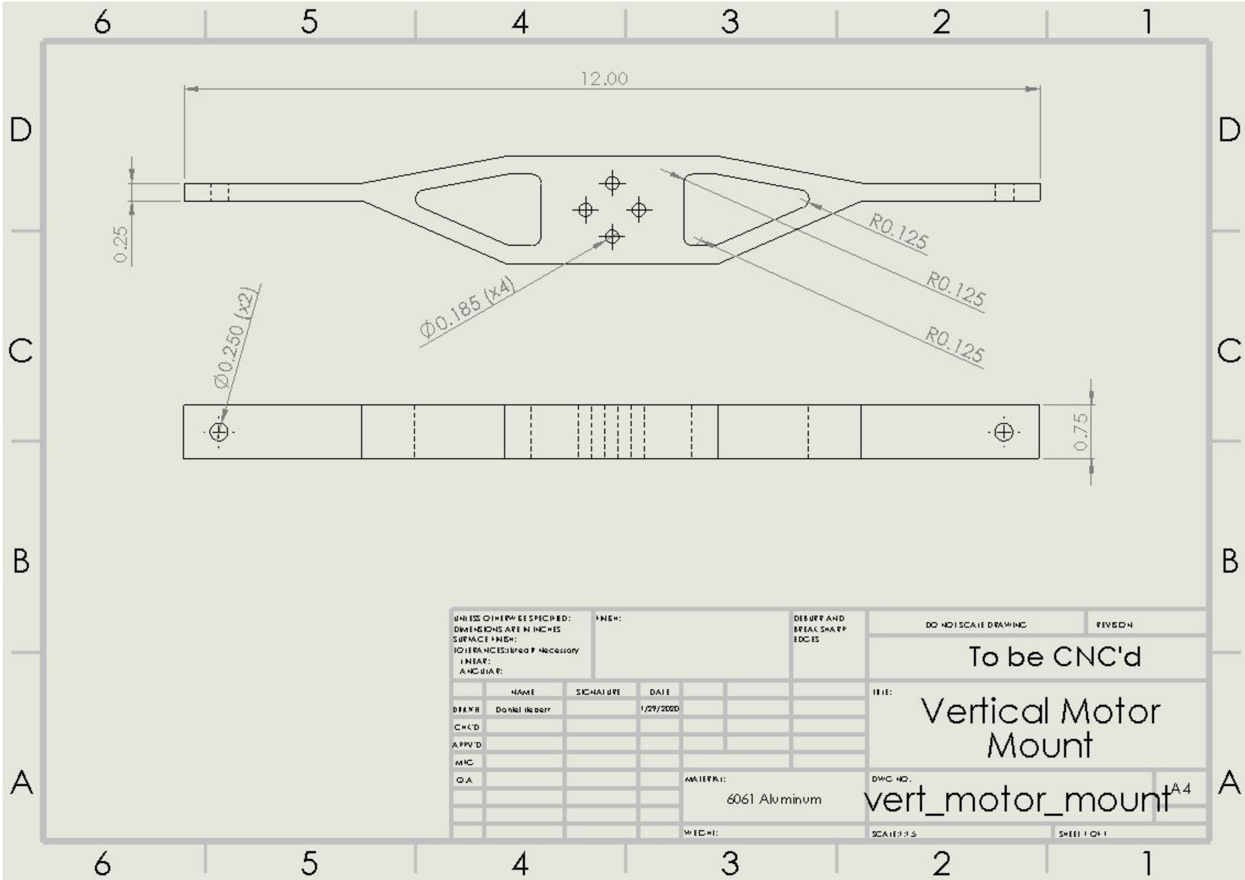

Figure 48: Vertical Motor Mount Drawing

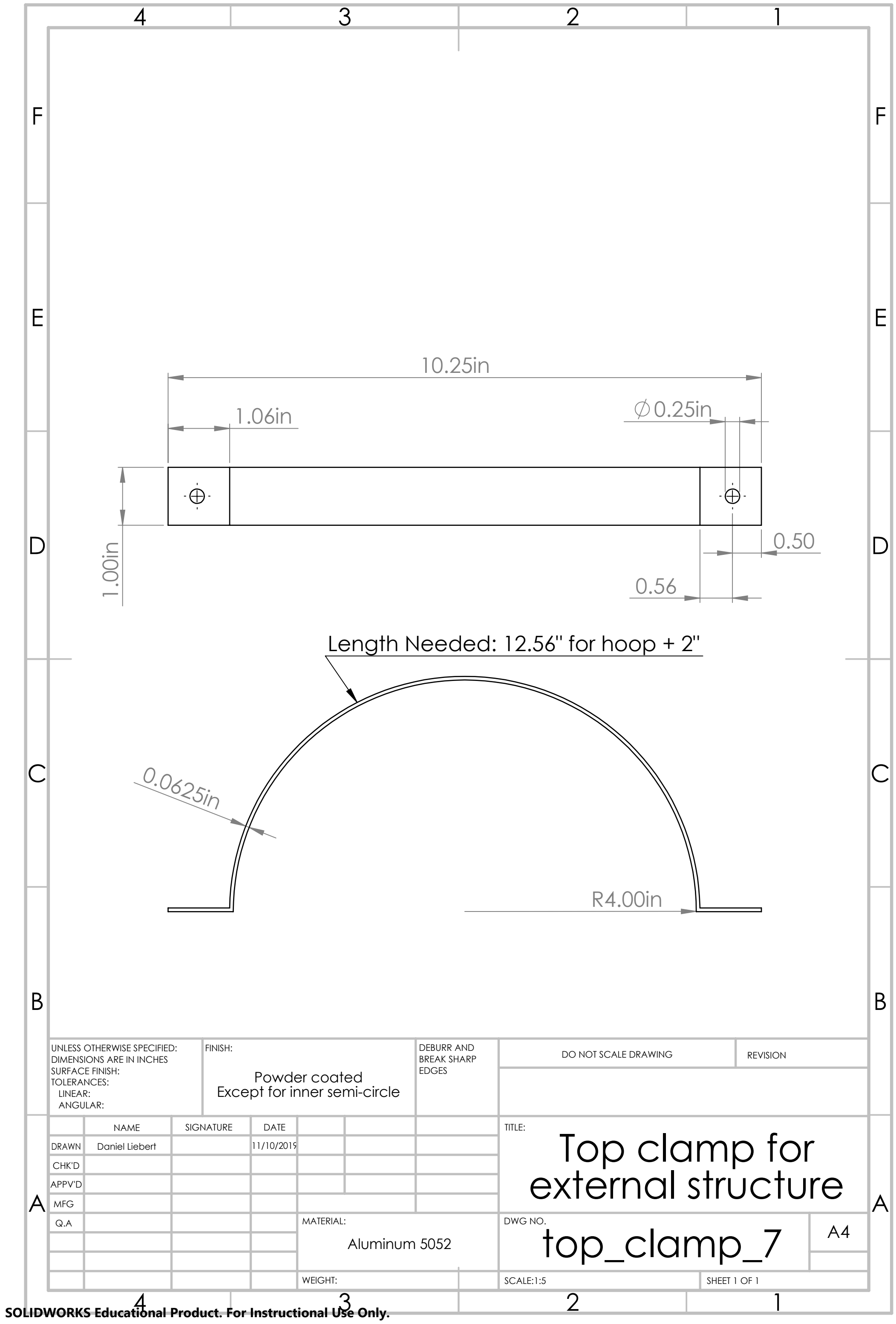

Figure 49: Top Clamp Drawing

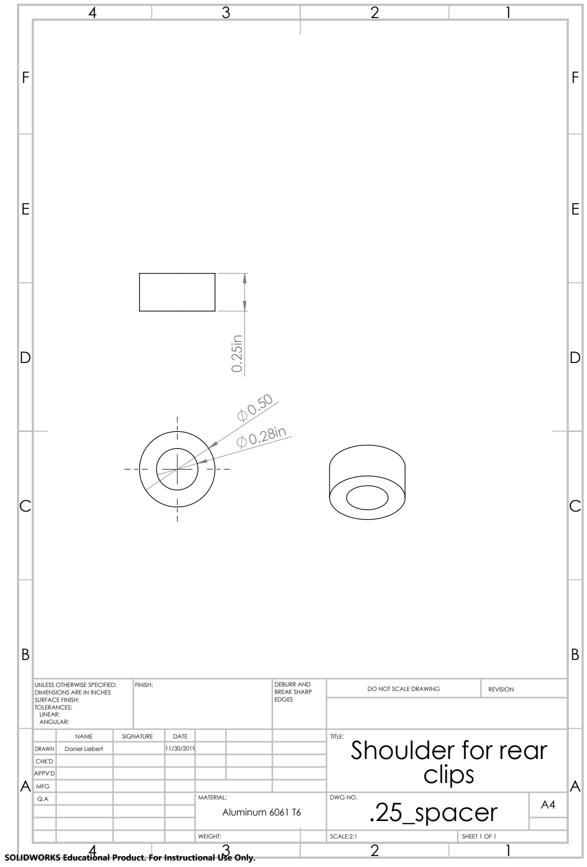

Figure 50: Front Spacer Drawing

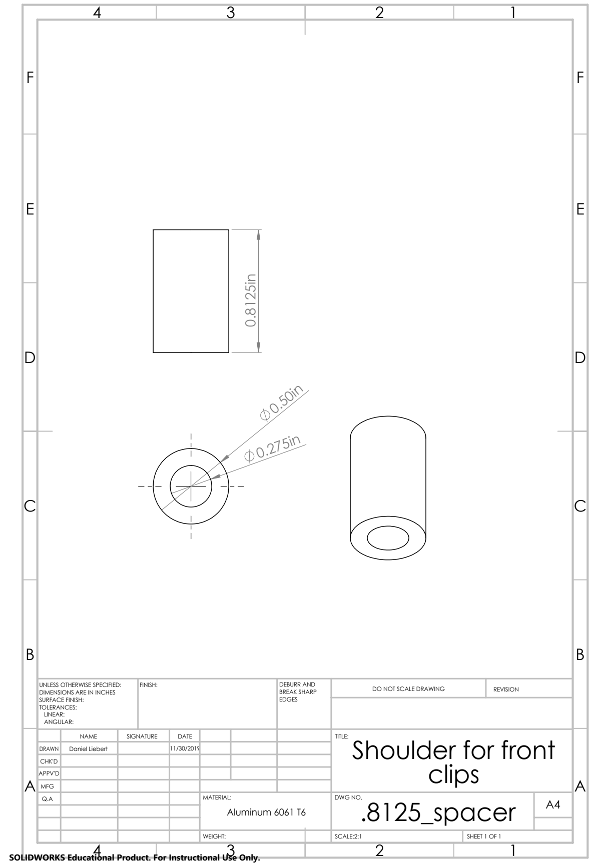

Figure 51: Rear Spacer Drawing

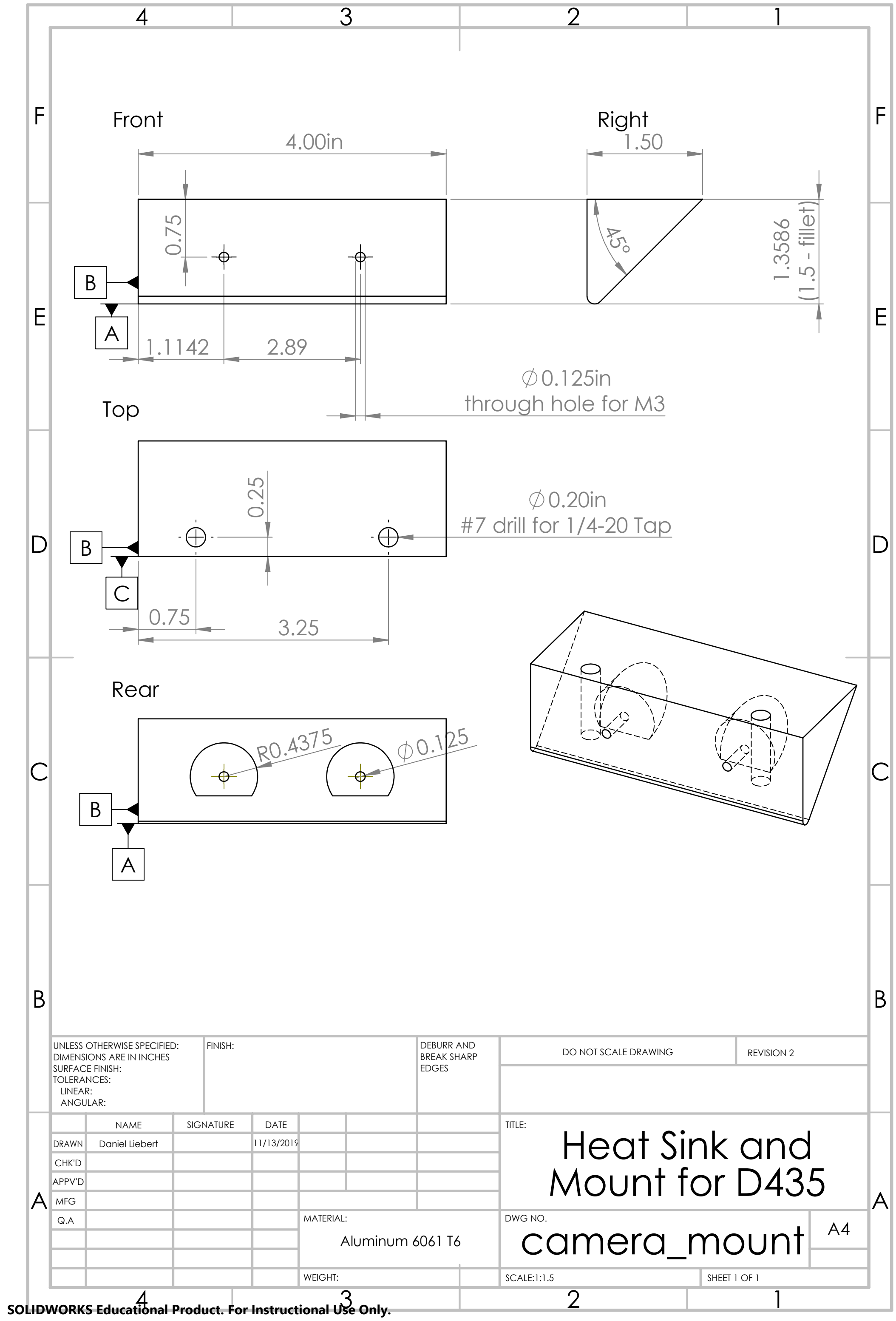

Figure 52: Camera Mount Drawing

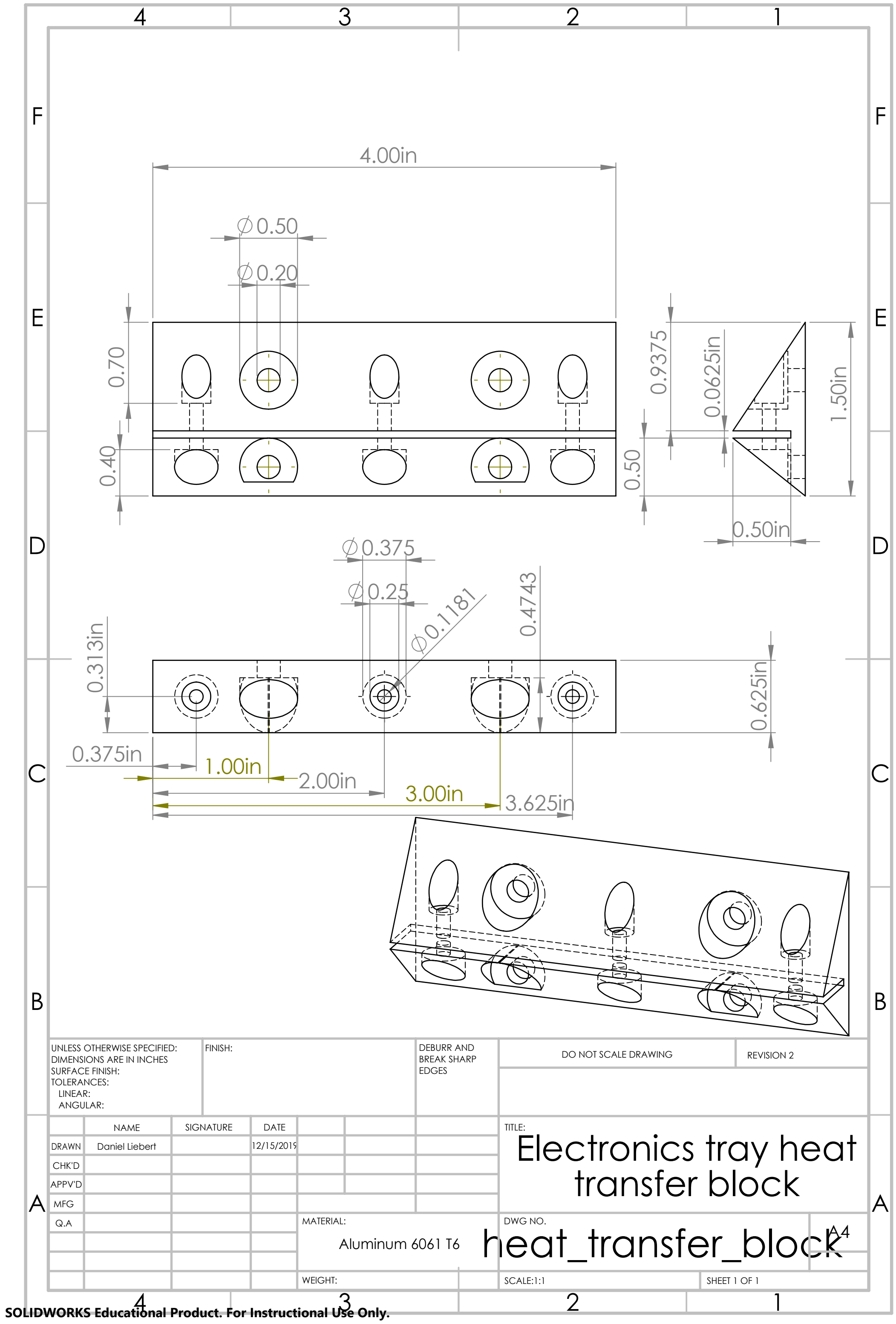

Figure 53: Electronics Tray to Endcap Mount Drawing