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I HEREBY RECOMMEND THAT THE THESIS PREPARED
UNDER MY SUPERVISION BY

Valeriya Chulyukina, Noah Villar, Kekoa Blair, Mandeep Singh, and Nathan Burke

ENTITLED

MARINE ROBOT SAMPLE RETRIEVING SYSTEM

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREES OF

BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING
AND
COMPUTER ENGINEERING

Christopher Kitts 6/9/2022

Thesis Advisor date

 06/14/22

Department Chair date

Department Chair date

MARINE ROBOT SAMPLE RETRIEVING SYSTEM

By

Valeriya Chulyukina, Noah Villar, Kekoa Blair, Mandeep Singh, and Nathan Burke

SENIOR DESIGN PROJECT REPORT

Submitted to
the Department of Mechanical Engineering
and
Computer Science and Engineering

of

SANTA CLARA UNIVERSITY

in Partial Fulfillment of the Requirements
for the degree of
Bachelor of Science in Mechanical Engineering
and the degree of
Bachelor of Science in Computer Engineering

Santa Clara, California

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Abstract

The exploration of our underwater ecosystems is critical. The aquatic ecosystem has a significant effect on human life, yet our understanding of the oceanic environment is severely lacking. Santa Clara University's Robotic Systems Lab contributes to subsea exploration through its investment in remotely operated vehicle (ROV) technology. This project was done with the guidance of not only professors in the Robotics Systems Lab, but also stakeholders from the US Geological Survey scientists and researchers from the Monterey Bay Aquarium Research Institute (MBARI). Our team goal was to further advance SCU's efforts by creating a sediment sample collection system consisting of a manipulator arm and sample storage container compatible with an existing SCU ROV. Our project has the potential to give researchers better access to submerged ecosystems and assists their efforts to understand and protect subsea environments in the future. We designed, built, and tested a prototype of a multiple degree-of-freedom arm and storage system for the existing Nautilus ROV, for safely manipulating and storing submerged sedimentary artifacts at 300 feet deep with a maximum dive time of 45 minutes. At the end of this project, we were able to see robust three degree of freedom movement of the arm within its anticipated workspace. We achieved a basic level of motion control of the arm which was successfully tested and evaluated within a testing tank. However, there is still need for additional testing and increased functionality of the mechanical and controls systems. The storage system for samples design needs a thrust bearing to better rotate and there is still much work to make the controls of the arm user friendly such as end effector control for depositing a sample into the storage system instead of doing all the movements manually.

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In addition, we would also like to thank Dr. Micheal Nuemann and Dr. Richard Schweickert, and the other researchers who volunteered their time to help us understand the world of underwater robotics and its applications. Dr. Neumann's Engr 180 course provided us with the basic knowledge of how underwater robots work and allowed us the opportunity to familiarize ourselves with one in Monterey Bay before making any changes to Nautilus.

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Section 1: Introduction

1.1 Background and Motivation

Water covers 71% of the Earth's surface, however relative to its physical prevalence and impact on our everyday lives, people understand very little of what lies below [1]. The ocean floor is less explored than the moon's surface; sonar only provides depth soundings data for nautical charts, giving little detail about the actual composition [2]. Even though we depend on large bodies of water for food and the huge role they play in our economy, we do not entirely understand them. We have never had the necessary resources to gain much knowledge about most of the oceans - the most we know about them are their depths.

Sea exploration has always fascinated humanity. The ocean's mystery has inspired exciting mythological creatures. From the demi-god Maui from Polynesia, who pulled an island out of the sea, to the Kraken sea monster from Scandinavian folklore, stories emphasize the mysteries of the deep that persist today [3,4]. Marine biologists discover more new species than any other scientist and are constantly finding more.

In 2020, almost two thousand new marine species were identified. These discoveries are exciting and essential in helping us understand how our world works and, now more critical than ever, the human-caused challenges facing the marine environment. Figure 1.1 is of *Eurythenes plasticus*, one of the new species recently discovered; its discovery is the first-time plastics have been recorded in a new species- giving us an idea of the omnipresence of plastic pollution [5].



Figure 1.1: *Eurythenes Plasticus*- the recently discovered giant plastic amphipod [5].

Richard Pyle, an ichthyologist who works with the Bishop Museum and the University of Hawaii, has discovered over 130 species in his diving efforts [6]. However, to continue to find out what lies at the depths of our oceans, people must go beyond the human body's limitations and explore the opportunities offered through modern technology.

With new species discoveries, geological findings have brought people closer to understanding the world, from the history of volcanic eruptions to earthquakes and being able to predict the future of such occurrences. Other significant marine findings have also been found from underwater exploration; half of our oxygen is produced from aquatic plant life, and the ocean assists in normalizing heat and weather [7]. The more we learn about the ocean, the better we can help it maintain its life-saving properties while the Earth changes under human influence. So far, we have seen ocean levels rising, temperature changes causing coral bleaching, shifting migration patterns of ocean life, and general pollution from things such as oil spills and plastics [8].

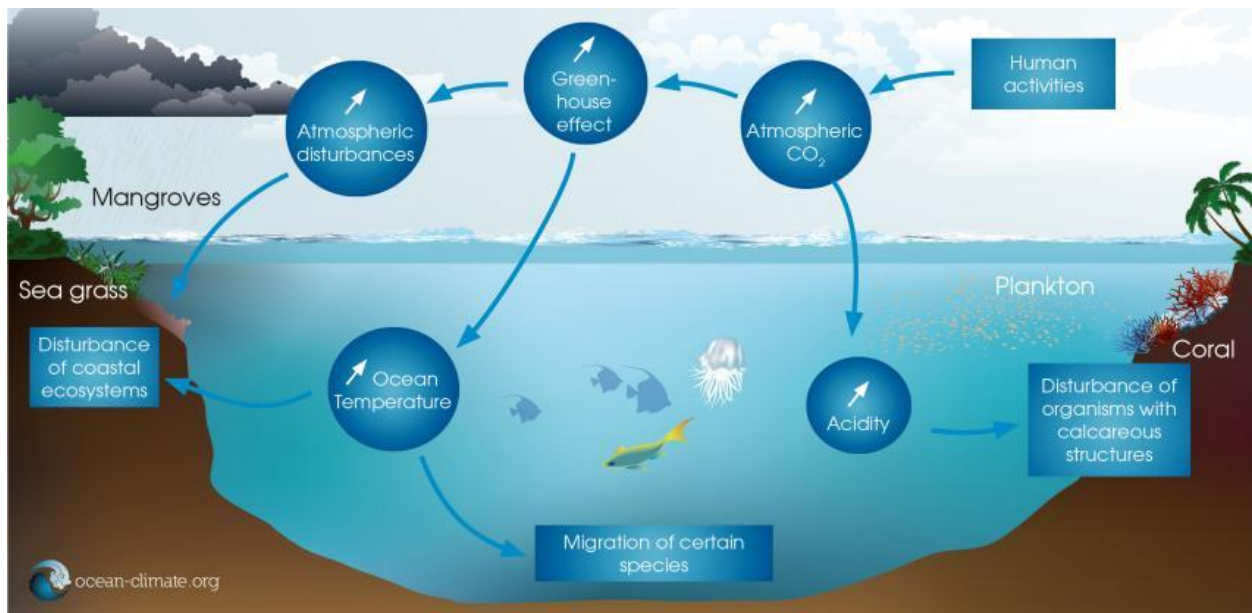


Figure 1.2. Illustration of some human effects on marine ecosystems [8].

Understanding, predicting, and fixing underwater issues can be assisted by advancing underwater robotics. Today, technology can aid in observing and sampling ecosystems in remote ocean regions to show the effects of human, seismic, and other geophysical activity. With analysis and substantial background knowledge, biologists and geologists can help put forward

policies to help dissipate and - in some cases - eradicate the effects of climate change and future natural disasters.

1.1.1 Underwater Robotics

Underwater robots take many forms that are suited for different tasks. Many scientists are interested in mapping the ocean floor and capturing current data for weather predictions. The four types of robots we use to gain insights into the ocean are Remote Operated Vehicles (ROV), Automated Underwater Vehicles (AUV), Buoys, and Saildrones. Each of these can take many different forms and sizes. These robots drastically reduce costs for oceanographic research compared to using research vessels. This is due to the vast size of the ocean, and the area limitations research vessels can cover. It would be extremely costly to take out vessels for expeditions continuously.

AUVs and Sail Drones are very similar in function and operation. AUVs are usually torpedo-shaped systems filled with instruments and mechatronics to guide the system. The main issue with AUVs is their ability to communicate with the research team during data collection. Since they operate underwater, they cannot transmit or get data during navigation. The advantages of an AUV are that it gives a very stable basis for measurements due to limited jostling from winds and waves on the surface. Saildrones, on the other hand, gain a considerable advantage from being on the surface. They have solar panels, which give them significantly longer deployment times and can carry much larger payloads of instruments. Sail Drones are also usually able to transmit real-time data and receive communications during navigation. This allows them to continue from mission to mission without being serviced.

Buoys are one of the most overlooked marine robotics systems. They are usually seen as stationary, but they drift based on ocean conditions due to the unique stack up of their anchoring lines. These anchoring lines consist of chains off the buoy, a section of non-buoyant rope, a section of buoyant rope, and finally, the concrete blocks and chain that secure it to the ocean surface. This unique collection of ropes provides the best drifting characteristics and longevity advantages. Buoys incorporate many data collection instruments to measure salinity, location, and altitude. These collections of sensors, when used over an array of buoys, can help predict weather patterns such as tsunamis, hurricanes, daily wind, wave, and tide reports.

ROVs are unique due to the variety of use-cases they can be utilized for, such as being a physical sampling system rather than being limited to adjusting a control system. ROVs are

already used in many research fields and can play many roles in different industries. These robots can be set up to interact with the subsea environment using multi-axis manipulators that can take samples, fix mechanical assemblies underwater, or even weld underwater. ROVs can range from a remote-control car to the size of a large SUV and are invaluable tools for industrial and research applications. These can range from inspection of critical infrastructures - such as underwater fiber-optic lines and oil pipelines - to discovering and interacting with sea life we have never interacted with [9]. Our ROV was previously used to map the surface of Lake Tahoe using Lidar sensors. Scientists determined that an asteroid impact occurred in the lake due to this expedition. There are many practical applications of ROVs that lead to quantifiable scientific outcomes.

1.1.2 SCU RSL and Research Facility



Figure 1.3: Triton RSL ROV [10].

The Santa Clara University (SCU) Robotics Systems Laboratory (RSL) has many ongoing projects, including Remote Operated Vehicles (ROVs)! The RSL has four main ROVs, Triton, Tessie, Nautilus, and - a unit from blue robotics - BlueROV2. In addition to these ROVs, the RSL has AUVs and various land and air robots. This large arsenal of robots allows multidisciplinary teams to expand their understanding of robotics and making through hands-on experimentation. The RSL is run by Dr. Kitts, and has made significant contributions to agricultural surveying with drones and rovers and the development of low-cost prosthetics and underwater research [10].

The RSL ROV fleet began with Triton, a student-led project mainly focusing its research in Lake Tahoe in conjunction with the United States Geographical Survey (USGS) and the

Monterey Bay Aquarium Research Institute (MBARI). The size of Triton often made it challenging to deploy and run missions because it required five people and specialized training to deploy. The Triton is four by four feet and weighs in at 250 lbs. However, this size does come with benefits, such as a 240 VDC tether system allowing it to operate up to 2000 ft without fear of running out of battery.



Figure 1.4: Tessie RSL ROV [10].

Tessie was another student-led project. It focuses on being easily deployable and is only a two-foot square with a depth limit of 500 ft. This smaller size factor allows for a crew of two to deploy it. Unfortunately, Tessie has recently been overshadowed by the BlueROV2, an affordable enthusiast-grade ROV with a depth range of 300 ft but much more intuitive and easier to maintain. These ROVs are battery operated and require minimal topside equipment to work but often lack the power to have advanced tooling [10].

Lastly, Nautilus is a hybrid of these two design philosophies. This ROV is entirely custom-designed and modular, as it has been changed many times over the last twenty years. The most recent dimensions in operating mode are 3ft x 2.5ft x 2 ft and weigh in at 180 lbs. This may seem heavy, but the excess weight is mainly due to the 50 lbs of ballast put in to allow for payloads in the future. Figure 1.5 shows Nautilus as it was before the start of this project.



Figure 1.5: Nautilus RSL ROV.

A better operating system can compromise the mission length, but the battery capacity is also higher than Tessie and BlueROV2. The Nautilus' lack of functionality and available space within its frame is what initially interested us. It is currently operational as solely an observing unit with minimal sensors employed. We plan to give it manipulation capabilities which are seen as an essential tool on many industrial ROVs. This will vastly increase the capacity of Nautilus.

1.1.3 Existing Products

The current capabilities of industrial manipulators are unhindered with seven or more degrees of freedom with similarly complex control systems. These controllers are often miniature replicas of the robot arm that copies whatever motion the controller makes. Our design will be utilizing an Xbox-style controller. Unlike industrial robots, our design will be much cheaper, smaller, and easier to deploy. A small research group should be able to attach our design to an ROV, deploy it, and have some samples within a few hours.



Figure 1.6: Professional Manipulator Controller [11].

The control and programming of these robots allow endless possibilities for research - often geological and zoological at the extreme depths they operate. Many of the implementations used by these industrial ROVs are highly specialized to give researchers the information they seek. These implements include sediment samplers, water samplers, and saline collectors. In addition, many other tools are used to take measurements while deployed, such as temperature, sonar, and seismic sensors. These instruments and sensors produce impressive data at these otherwise unexplorable depths. At relatively shallow depths for our midsize ROV, we will focus on instruments rather than sensors due to sensor data being very similar to the surface and shore measurements, while the scale of our deployments is in deep water [12].



Figure 1.7: Blueye X3 Mini [13].

There are many different classes of ROVs with manipulators that can be purchased for various budgets and use cases on the market. On the more hobbyist and small-scale end of the spectrum, you have something like the Blueye X3 Mini ROV with a fixed gripper that relies on the robot's movements for positioning the gripper. A small ROV can be used for visual inspection, retrieving small objects, cutting tangled ropes, or collecting a single object as a sample. The ability to swap the gripper for many different tools expands the number of possible use cases. It is a low-cost, portable solution for most simple underwater tasks.

One class above price and functionality would be something like a BlueROV from BlueRobotics. BlueRobotics sells a gripper called the Newton Subsea Gripper, allowing the BlueROV to have similar functionality to the Blueye X3. However, unlike the Blueye X3, a larger, more expensive ROV is modular and can be adapted to use a wide range of larger attachments. The Newton Subsea Gripper is just one example that gives the ROV more excellent capabilities. This class of ROV is too expensive and not portable enough for a hobbyist and is more likely to be used by research institutions and universities. The modularity also allows for flexibility in budgets and use cases.



Figure 1.8: BlueROV with Newton Gripper [14].

In terms of working-class ROVs, there are arms such as the Hydra-UW3, which can only be mounted on large, industrial ROVs. These arms have many degrees of freedom and are capable of much more difficult operations due to their high cost and strength. These arms have to endure extreme depths and much higher loads than our ROV. The strength output of an arm like the Hydra-UW3 can move large objects and operate heavier underwater machinery such as sediment push cores which require much more force than a small or midsize ROV can output.

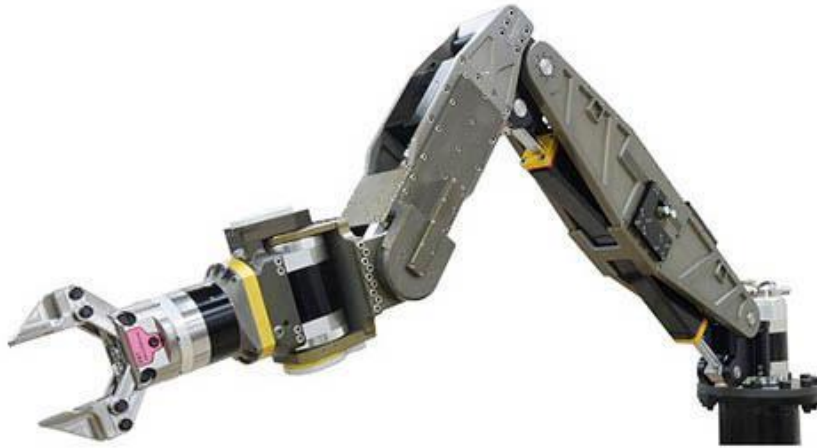


Figure 1.9: Hydra UW-3 [15].

Our robotic arm will be used for research. Our goal is to keep the design simple, lightweight, and portable while adding more degrees of freedom than other small-scale arms. The BlueRobotics and Blueeye grippers rely on the movement of the ROV to collect samples or complete tasks. Our arm can move independently from the ROV and store multiple samples in a dedicated sample storage system, giving it capabilities usually only available on industrial ROVs. Our ROV can be deployed on a small boat while also collecting and storing multiple samples, combining some of the functionality of a large, industrial ROV with the ease of transport, low cost, and deployability of a small research ROV.

1.2 Statement of Goals

For as long as the Nautilus has been operated, its only capabilities have been to remotely maneuver underwater and take low-quality images and videos of the submerged objects and lifeforms it encountered. The Nautilus has been used for geological research efforts in Lake

Tahoe, mainly for studying the sedimentary features beneath the lake. The geological landscape of our country's lakes is integral to our understanding of glacial patterns in the United States [16]. Today, we know that Lake Tahoe was created during our last glacial period - the Ice Age - nearly one million years ago [17].

Until last year, Nautilus had not been worked on in decades and had not had the opportunity to incorporate newer technologies into its functionality. In 2021, students identified this opportunity and fixed Nautilus to be once again a functioning ROV: by reconfiguring the thrusters to a new control system [18]. Now that Nautilus was operable and “modernized,” its users have expressed their desire for more functions. Operators of the Nautilus had never entertained a manipulator addition, despite the potential findings that it might bring. That is why in 2022, within the existing space in Nautilus’ frame, our team chose to add object manipulation and storage capabilities to the Nautilus ROV.

The completed manipulator and storage system are intended to provide a practical and valuable means for our stakeholders to collect submerged sedimentary samples for their research efforts using the Nautilus ROV. The system is minimally invasive to the Nautilus’ existing field of view, so there is no sacrifice of imaging and observation capabilities that its users are accustomed to. It is paramount to our stakeholders that our capability enhancements do not come at the expense of those that already exist, the onboard camera and the Nautilus’ neutral buoyancy, so our manipulator and storage system were designed to minimize camera view obstruction. We ensured that the additional buoyant forces would not impact smooth operation.

Our leading team goal for the new system was to smoothly integrate with the Nautilus ROV hardware structure and usual operation. All new parts of our system (Manipulator, Electronic Storage Compartment, and Electronics/Controls Tube) fit within the existing Nautilus frame and are strategically placed so that the current buoyancy is minimally impacted. We integrated the new manipulator control modules with the existing Nautilus control module (Arduino MEGA 2560). Both can be controlled via the existing single-tether that runs from the computer interface to the Nautilus. A new controller, solely for manipulator control, was integrated into the existing user interface on the software side. Furthermore, we implemented a system of control by which the user will maneuver the manipulator by controlling the X, Y, and Z positions of the tip of the claw, and included two default positions for the claw tip, one at the folded “home” position and one position over the sample storage unit for sample deposit. Finally,

we included a failsafe program in place to prevent the claw tip's XYZ coordinates from colliding with the existing frame or the sample storage unit. The controls require two Nautilus pilots, one to control the ROV, and the other to control the manipulator, and the existing interface, including the Heads-Up Display (HUD).

The Santa Clara Vision Statement intends for students to build a “more humane, just, and sustainable world”. This is a main driver of our goal; to aid in the types of research mentioned under the background and motivation section of this paper. Our lakes and oceans hold essential information about the history of our local environment. Understanding of our past allows our future leaders to better recognize the patterns that stripe history through the bad and the good. Knowing these patterns will ultimately enable us to see them reemerge; in our recent history. Environmental changes can be seen in physical sediment samples and enhanced imagery analyzed by marine scientists. From looking at the health of ecosystems to characterizing sediment, plant and animal changes, we can assess long term environmental change.

Section 2: System Description

2.1 Customer Needs

Our stakeholders fit into two main categories, aquatic-based scientists and ROV-focused engineers. We spoke with Dr. Rick Schweickert and Dr. Geoff Wheat from the scientist category, Jeff Ota and Thomas Adamek from the engineering category, last year's senior design team, and Dr. Chris Kitts, who oversees the Nautilus operations. We also briefly met with Chad Bulich, the senior design lead for Nautilus 20+ years ago, and Bill Kirkwood, another talented engineer with ties to the ROV projects in the RSL.

2.1.1 Customers

Dr. Christopher Kitts is the main stakeholder in our project as he is the director of the Robotic Systems Laboratory at SCU. His experience as an SCU Professor and Director of the RSL has given him significant insight into the various ROV projects within the RSL. In addition, he has given us guidance on what can best serve the researchers who take advantage of our lab.

Dr. Rich Schweickert is an emeritus from UN Reno who has worked with the RSL and Dr. Kitts for about 20 years, making annual trips to Lake Tahoe. In addition, he has worked very closely with the Nautilus ROV doing multiple imaging missions.

Dr. Micheal Neumann is a long-time Santa Clara researcher and adjunct professor who works with the aquatic side of the RSL a lot. His oversight of RSL missions to Lake Tahoe and Monterey has helped scientists and students gain insights into these ecosystems.

Dr. Geoff Wheat is a researcher from Monterey Bay Aquarium Research Institute and has much experience with ROV, which he is gracious enough to share with us. His connection to the RSL has made him a tremendous first-hand resource for students to learn about professional ROV deployments.

2.1.2 Customer Questions

Our primary focus in the interviews was different for each group; with the engineers, we focused on common robotics pitfalls and setting realistic expectations; while the scientists had great insight into this, they more helped us focus our project based on their needs and wants for viable research tools. Nevertheless, both groups gave us great insight into our project potential and what we could engineer to make it useful in the industry.

The questions we posed to scientists revolved around sample type, size and identifications to best make our tool useful for them. Our background research could tell us the types of materials that exist on the sea and lake floor, but not what is useful for their specific research. Often the mode of their research is changing and leads us to create places for modification throughout the design process. Later the engineers and ROV experts had a lot of advice on technical specification goals. The main parameters we had to decide upon based on these interviews were degrees of freedom requirements as well as reach parameters. The technical specs we had to set up were mainly big picture things such as placement of the arm and mechanism the storage will work on. Our preliminary ideas had the arm reaching down from the bottom or from the front, and storage systems that require rotation or translation. Our main goal was to gain guidance on the things that can only be learned from experiences, we can research and calculate servo requirements thus it would waste the time of our experts but an adequate working window is something you can only gain from experience.

2.1.3 Analyzing Customer Responses for Product Specifications

Once we talked to all the stakeholders, their requests and priorities were pretty standard, but also some additional suggestions or asks that were more unique. We summarized this information into Table 2.1, along with a rating reflecting their relative importance that our stakeholders indicated; 5 being very important or a need, and 1 being low priority to include. This table gave us an even clearer idea of what existing designs are lacking, and where our project can really excel. Stakeholders all seemed to want something that can provide useful data, that is otherwise inaccessible, in an easy and time efficient way.

Table 2.1: Stakeholder Requests and Their Associated Relative Priorities.

Request	Priority
Collect multiple samples on one excursion	3
Timely (collect multiple samples in the span of one morning)	5
Able to collect rocks, mud and silt (various types of sediment)	5
Samples up to 2x2x2in	2

See the layering in a couple inches of sediment	2
Function at a depth of 300ft	2
Grip and break off thin rock layers	2
Store samples during excursion	5
Accurately identify and record coordinates of where a sample has been taken	4
Compatibility with existing tools/ potential for modular claw attachment	3
Can move or leave instruments	1
Reduced effects on ROV's motion and stability	5
Doesn't affect ROV's neutral buoyancy	5
Visual readings of ROV's distance from the ground on decent	3
Ability to identify size and color of things seen in the camera (better imaging)	1
Manipulator system is fully removable	5
Manipulator system is easy to store and transport	4
Thorough documented procedures from attaching, using, removing and storing	4
Takes less than 3 tries for a trained user to achieve a given task	4
Anyone can be trained to use it/ not overly complicated to control	3

*It's important to acknowledge that in the field, an arm is not standard or a "real" way to sample mud or sand. Push or screw cores are used in cases to see layers in the sediment- not deemed necessary for our stakeholders' purposes.

2.2 Product Specifications

After analyzing the customer responses, we made a list of quantifiable specifications for our final product. We also included other limitations not specified by customers but by our budget, resources, and timeline in this list. We used these as parameters throughout the design

process of our product to keep us on track and make sure that we were meeting the needs of our customers. These requirements were also translated into design parameters for the matrices in Section 3.2 so that we could rank design options against one another.

2.2.1 List of Requirements

1. Collect 3 samples in 45 min
 - a. Capable of lifting rocks and sediment of 2 in³ volume
 - Assume maximum weight of sample to be 1.6lbs (See Appendix D for Calculation)
2. Maintain neutral buoyancy and center of mass
 - a. When the arm is out, make sure that the ROV motion is still stable and easy to control
3. Works at 300 ft depth (analyze effects of pressure)
4. Removable within one hour
 - a. Independent system
 - Has neutral buoyancy
 - Has its own battery and controls tube
 - Self-contained in one electronics tube
5. Ability to reach 80% of visible workspace
6. Potential to be made compatible with existing tools
 - a. Claw is removable from rest of arm, allowing for modular claws
7. Cost effective (fits within our budget of \$4990)
 - a. Use scrap parts when possible
8. Minimize obstruct view of camera
 - a. 150° unobstructed view
9. Create manipulator specific controller
10. Easy to use for new crew (include a procedure)
 - a. Doesn't take more than 3 tries for trained user to collect sample
11. Within our budget of \$4990
12. Manufacturable within the Winter Quarter (about 3 months)
13. Maximizes environmental sustainability (use scrap parts and materials where possible)
14. Meets Santa Clara Universities safety requirements (See Appendix C for full hazard

assessment)

2.3 System Overview

Figure 2.1 depicts how we envisioned the upgraded Nautilus to function and displays a general operational outlook of the combined systems. The yellow tether is spooled from the boat and is the control mechanism for the ROV. Data packets are sent and received via this tether. However, no power is sent through it as the ROV is battery powered. As had previously been capable, the robot will be fully operational and able to sufficiently maneuver for a maximum of 45 minutes at a depth of 300 feet underwater before it has to surface for battery recharging, assuming responsible operation. Likewise, our manipulator and storage system is designed to operate at these specified time and depth limits. Before using its existing control system, the Nautilus could only maneuver within a body of water and send a live video feed of what was being seen. However, physical samples can now be collected with our new manipulator, which is critical in studying many scientific fields. These samples can be stored in our added sample storage mechanism and brought back to the expeditioners above water.

The process of sediment sample collection involves two pilots, one with control over the Nautilus ROV movements and one with control over the manipulator and sample storage system. The Nautilus pilot will generally maneuver the ROV as usual, using the camera to identify a sedimentary object or soft surface to collect a sample from. Then, depending on the location of the desired sample (elevated or on a flat bottom), the ROV can be maneuvered above or in front of the sample while the arm either extends the arm forward or drops it below the ROV frame. With coordination between both pilots, the sample can be collected through ROV and manipulator maneuvers. Then, the claw can be maneuvered to the drop point using coordinates on HUD and deposited the sample into the storage system, where it is safely stored until the ROV is retrieved from the water.

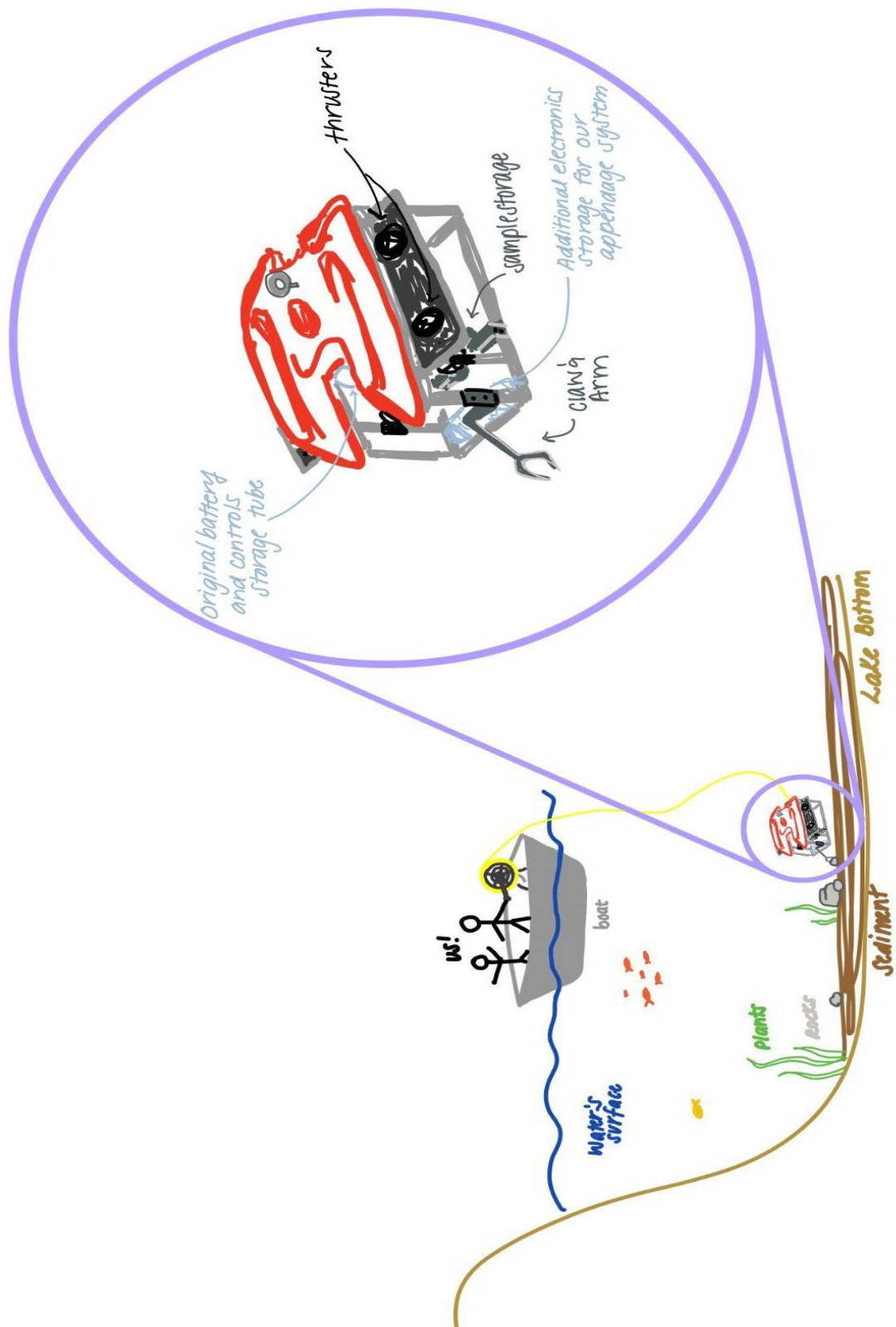


Figure 2.1: Operations Sketch.

Section 3: Subsystem Level Analysis and Design

3.1 System Design & Subsystem Identification

Considering the system requirements presented by the interviewed stakeholders and the necessary operations of the manipulator, we have designed our sample collection system with three specific subsystems in mind:

1. The manipulator arm: this subsystem includes all parts of the manipulator, not the claw attachment itself. It has 3 degrees of freedom, two servos used for vertical rotation and one servo used for horizontal rotation. The arm includes a mounting section where the first arm link and horizontal rotation servo are attached to the Nautilus frame, and it has a mounting section on the other end where the claw assembly is mounted.
2. The manipulator claw: this subsystem includes the triangular clam scoop claw halves, the servo attachment, and mechanism structure, and the mounting piece to attach the subsystem to the end of the arm. Within the subsystem, the opening and closing of the claw is the only mechanical action.
3. The storage container: This subsystem includes the cylindrical, four-section storage container and the newly added crossbar that fixes the container to the existing Nautilus frame. A rotational mechanism allows user-triggered rotation of the storage container, controlling which storage section is exposed. Note that only three sections may be in use at a time, as one section will be open at all times.
4. Electronics Storage Tube: This subsystem is not officially stand-alone, as it plays a role in powering and controlling the other three subsystems. The storage tube houses our added electrical components, battery, and the software that controls the arm.

The locations of each subsystem can be seen in Figure 3.1 below.

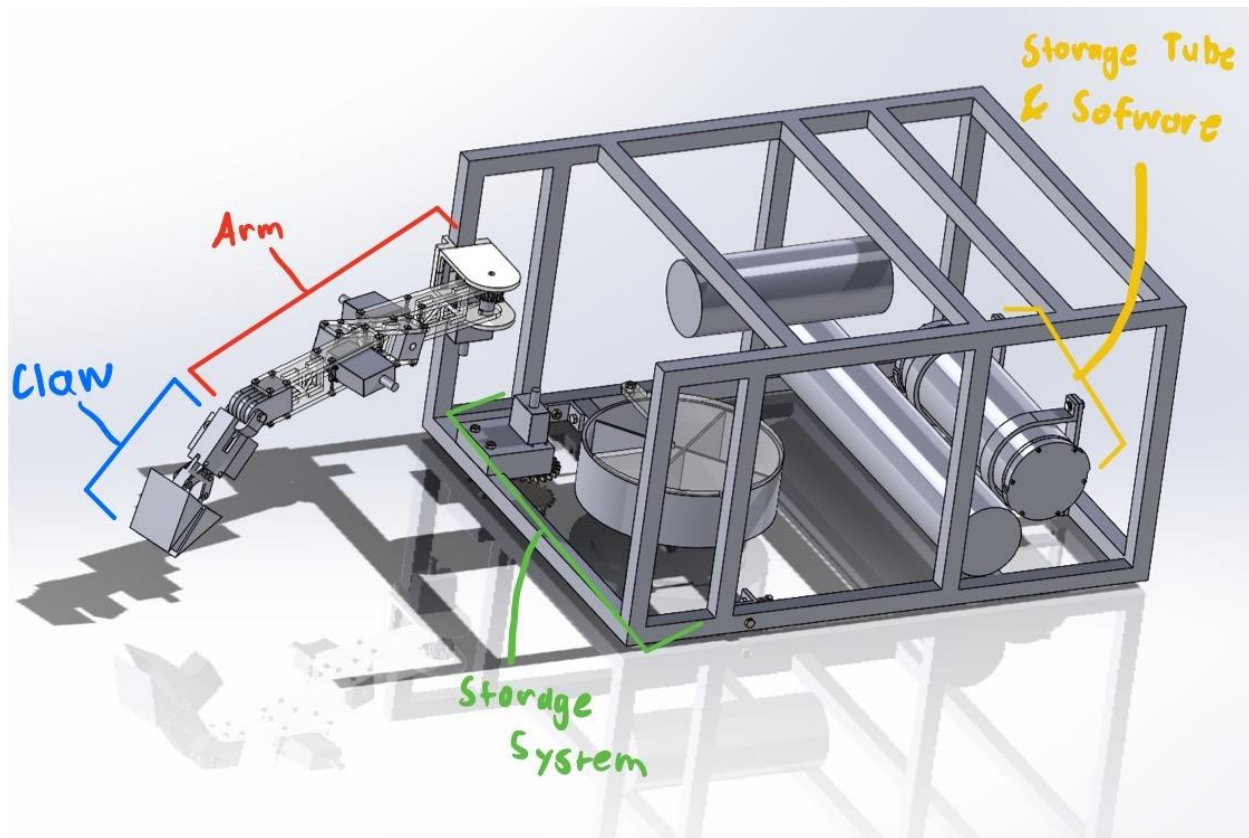


Figure 3.1: Mechanical Configuration with Color-Coded Subsystems.

3.2 Subsystems Design Selection

The following matrices assisted our design decisions for each subsystem (Arm, Claw, Storage, and Electronics/Software). Each matrix includes a list of parameters relevant to our project's success that we considered. We considered the parameters based on the design requirements that we decided on based on our stakeholder interviews. For example, we found that parameters such as "manipulation ability" and "ability to collect rocks" were fundamental to the stakeholders. However, we also included parameters that we felt were essential considerations for practical purposes, such as "manufacturability" and "cost." The designs for each subsystem are discussed in-depth in this section, and we provide visual examples of some designs that we considered. For visual assistance, the visuals associated with each subsystem are colored according to the legend in Figure 3.2.

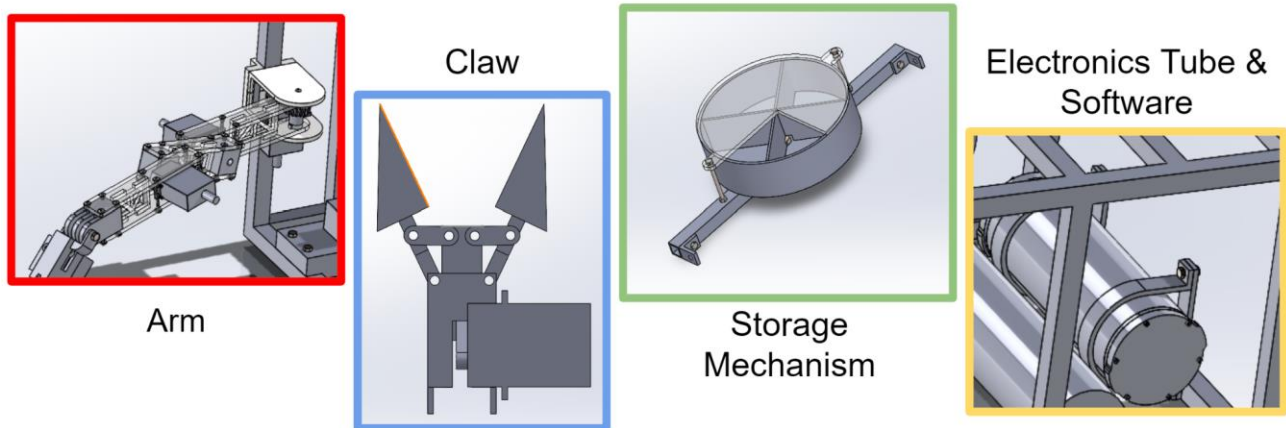


Figure 3.2: CAD Images of all Subsystems with respective labeling.

3.2.1 Arm

The Arm proved to be one of the most critical subsystems in the project. The Arm design would determine several important parameters for the manipulator, including degrees of freedom (DOF?), range of motion, and a maximum allowable load of the samples collected. Therefore, this subsystem required the most consideration and preliminary testing before choosing a final design.

Considering underwater manipulator arms currently on the market, the apparent trend was that the vast majority of what exists is geared toward deep-sea, extreme-budget endeavors in the harshest of underwater environments. It was found that these options, such as the Deep Trekker Two Function Arm, the TMI-Orion Electric Manipulator, and the Arm 5e Mini have impressive capabilities and clenching force but are significantly more expensive, with some requiring research group interest to obtain pricing quotes. Beyond the cost of the manipulators themselves, integrating each with a specific underwater ROV is also the cost. Although the Deep Trekker Two Function Arm has a cost of only \$1700, it would not be a simple process to integrate it into the existing Nautilus ROV, requiring it to be securely mounted to the frame and also be controllable via the existing tether and Arduino Mega UNO board within the Nautilus's electronics tube. Our manipulator system will not only include the Arm, but the storage system and electronics will all be fully integrated and usable on the Nautilus with a total budget of \$5000.



Figure 3.3: Existing Underwater Manipulator Arms from left to right: Deep Trekker Two Function Arm (Deep Trekker), TMI-Orion Electric Manipulator (TMI Orion), Arm 5e Mini [21, 19, 20].

Table 3.1: Analysis of three Manipulator Arms available on the market.

Existing Deep-Sea Manipulator Solutions	Deep Trekker Two Function Arm	TMI-Orion Electric Manipulator	Arm 5E Mini
Claw Force	70 Lbf	50 Kgf	25Kgf
Underwater Weight	Neutral	8Kg	15 Kg
Jaw Width	5"	4"	4"
Depth	656 ft	1500ft	900ft
Power Source	12V DC	24V DC	24V DC
Price	\$1700	N/A (Very Expensive)	N/A (Very Expensive)

Of the parameters considered, the range of motion was the most important one considered. Above all, our manipulator's arm's smooth and practical function would provide the most valuable product for our stakeholders, and trading other parameters such as size, weight,

and simplicity would be worth it. Three-arm designs were considered, each with dramatically different looks and functionality; They are displayed below in Figure 3.4.

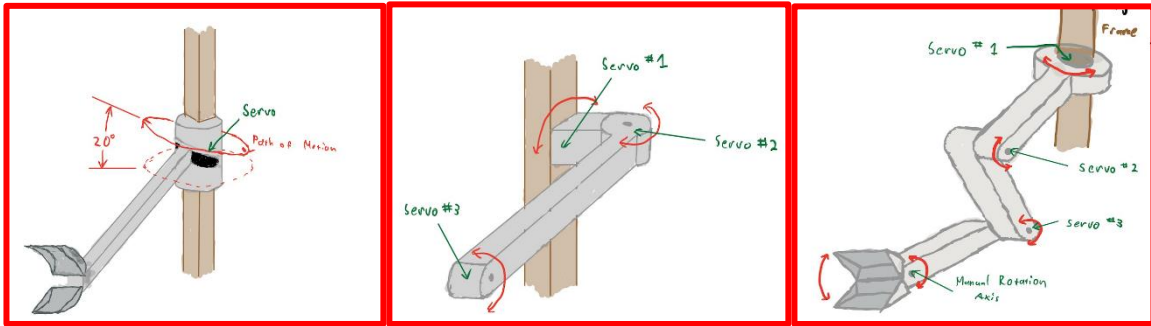


Figure 3.4: From left to right, Design #1, Design #2, and Design #3 of the Manipulator Arm Subassembly.

Design #1 maximizes simplicity with a single link that pivots at a certain angle (20° arbitrarily chosen) and allows for both vertical and horizontal translation within the same motion. As a result, the pilot would have only one servo to control, and the movement of the arm could be much more easily integrated into the software and programmed into the Nautilus's remote control. However, its motion capability is limited by its one degree of freedom.

Design #2 involves two degrees of freedom, with two servos located near a single pivot rotating the arm in two different planes. In addition, this arm design involves a single link of fixed distance mounted to the ROV frame with what is effectively a ball joint. This feature provides a significant upgrade to Design #1's range of motion while relatively maintaining the previous simplicity.

Design #3 maximizes the movement capability of the arm while sacrificing the desired lightweight and specific control features. The three-link setup of this design allows for a variable and controllable arm reach and more flexible motion. This sort of motion would allow for better movement when collecting subsea sedimentary samples and a more comprehensive range of reachable drop points within the frame of the Nautilus, where the sample storage system is located. Of course, a three-link design requires more parts, including servo motors and structural supports. Therefore, weight and control assistance become essential factors in this design.

A preliminary test was conducted on the three designs to analyze and compare the range of motion for each. Using MATLAB plots, the workspace area of each arm design was

visualized. First, the base workspace plane, shown in Figure 3.5, was defined. The base workspace plane is the plane coincident with the bottom of the Nautilus's frame, where most sample collections are expected to occur. From analyzing the workspace of each arm design in this plane, a visual map of each range of motion is obtained.

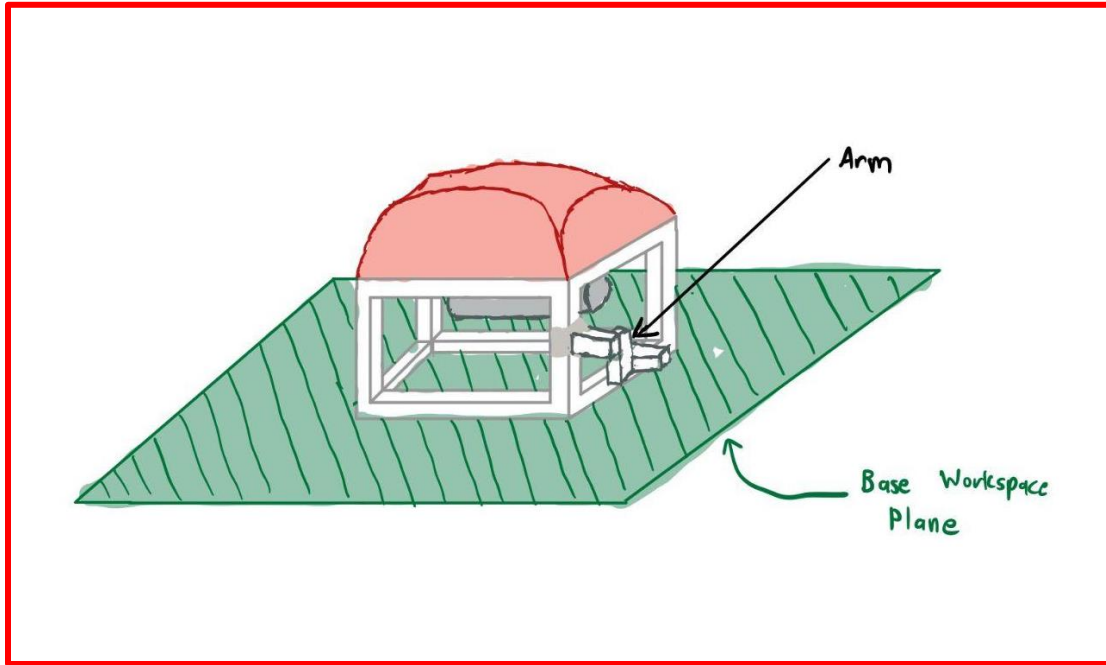


Figure 3.5: Base Workspace Plane shown with respect to the Nautilus reference frame.

Design #3 emerged from the MATLAB plots as the clear best option for maximizing the range of motion. As seen in Figure 3.6a, Design #1 only interacts with the base workspace plane at a single point, given that it has a fixed, single path of travel. The consequence of this design is that any adjustments made when attempting to collect a sediment sample will need to be made by the Nautilus using its thrusters. The arm itself will have no capability to adjust within the base workspace plane. This would limit the environments in which sample collection could occur and make navigating through currents and undersea external forces extremely difficult. Design #2 would face a similar issue, seen in Figure 3.6b, with the range of motion limited to a single arc curve. Although having 2 degrees of freedom allows for more control over movements, the design involves only a single linkage, which means that the maximum reach is limited to the length of that linkage. Design #3, with telescoping capabilities given by three links, has the most dynamic range of motion within the base workspace plane, shown in Figure 3.6c. The arm itself

would be able to adjust during sample collection and act independently from the movement of the Nautilus. Table 3.2 displayed the final rankings of each design and justified the choice of a three-link arm system in Design #3.

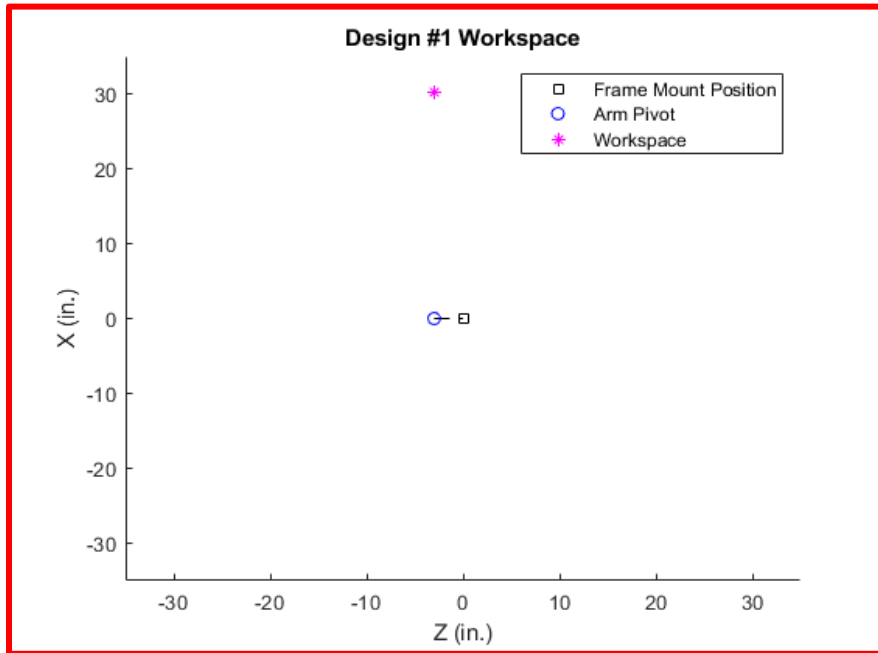


Figure 3.6a: MATLAB plot of workspace in Base Workspace Plane for Design #1.

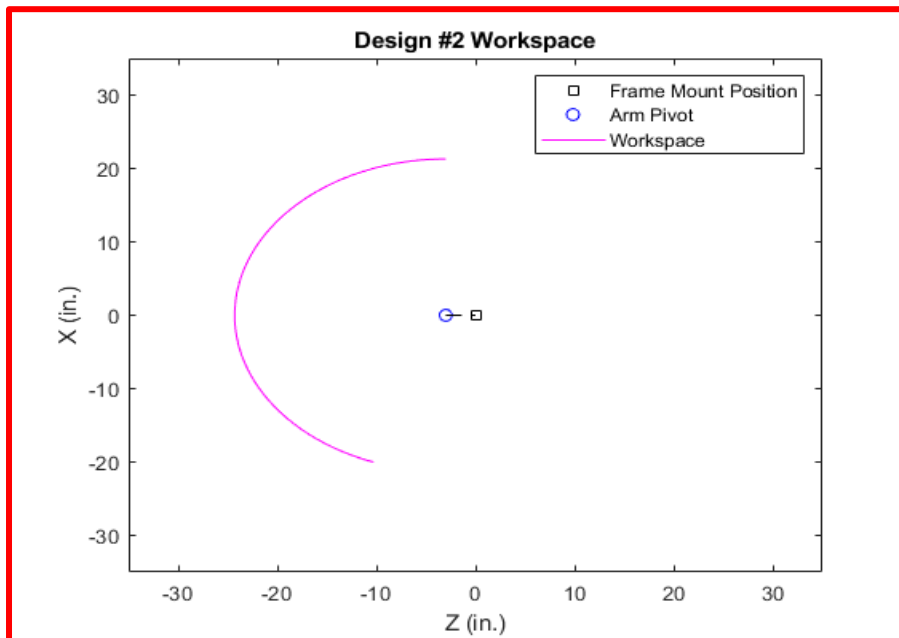


Figure 3.6b: MATLAB plot of workspace in Base Workspace Plane for Design #2.

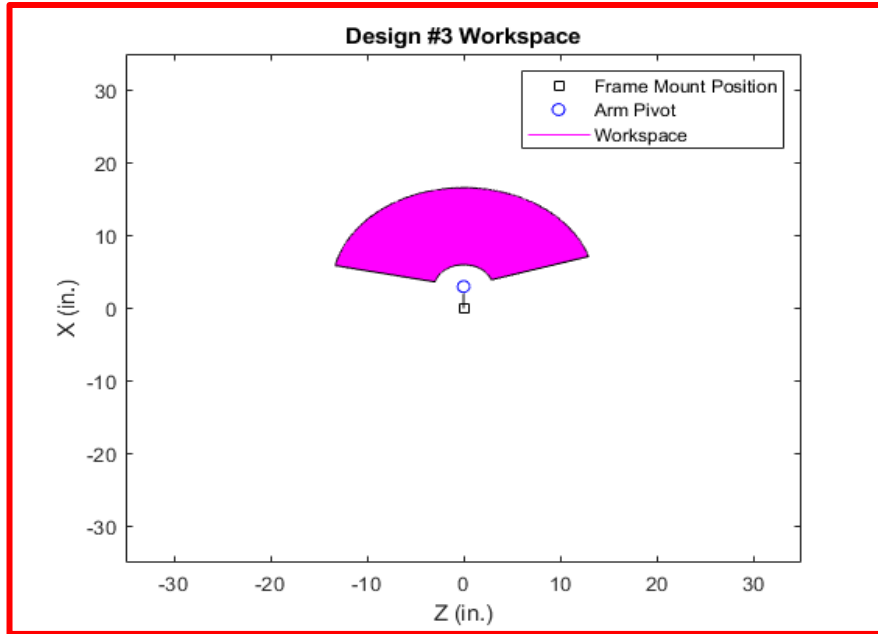


Figure 3.6c: MATLAB plot of workspace in Base Workspace Plane for Design #3.

Table 3.2: Arm Design Final Rankings.

Arm Design					
	Importance (weight)	Design #1 - 2 DOF, Hand & Elbow Structure, Swings diagonally for vertical and horizontal movement	Design #2 - 3 DOF, Joints act like a Hand, Elbow, and Wrist	Design #3 - 3 DOF, One rotational joint for horizontal movement, Two rotational joints for vertical movement	
Compatibility with Existing Tools	0.1	3	2	3	3
Cost	0.05	3	2	1	1
Manufacturability	0.1	3	1	2	2
Manipulation Ability	0.15	1	2	3	3
Range of motion	0.35	1	2	4	4
Weight	0.05	3	3	1	1
Size	0.05	3	2	2	2
Simplicity	0.05	4	3	2	2
Manueverability/ Ease of use	0.1	2	2	1	1
Total Weighted Score		1.95	2	2.75	
* Each ranked on a scale of 1-4					

As previously mentioned, the three-link set-up of Design #3 presents a significant weight issue for the parts of the arm. To counteract this, it was decided to incorporate the use of Blue Robotics Subsea Buoyancy Foam (Figure 3.7) into the arm subsystem. Using the specifications of buoyancy force for the foam given by Blue Robotics Inc., the needed volume of foam was

calculated using the equations seen in Appendix D. The buoyancy force provided by the Blue Robotics foam ensures that each servo motor will not experience excessive torque upon movements underwater. In addition, each arm link also contains negative space between the fixtures that provide a convenient space to attach the subsea foam. Figure 3.8 displays this feature of one of the links in our design and the finished look once the buoyancy foam was added.



Figure 3.7: Blue Robotics Subsea Buoyancy Foam: R-3312.

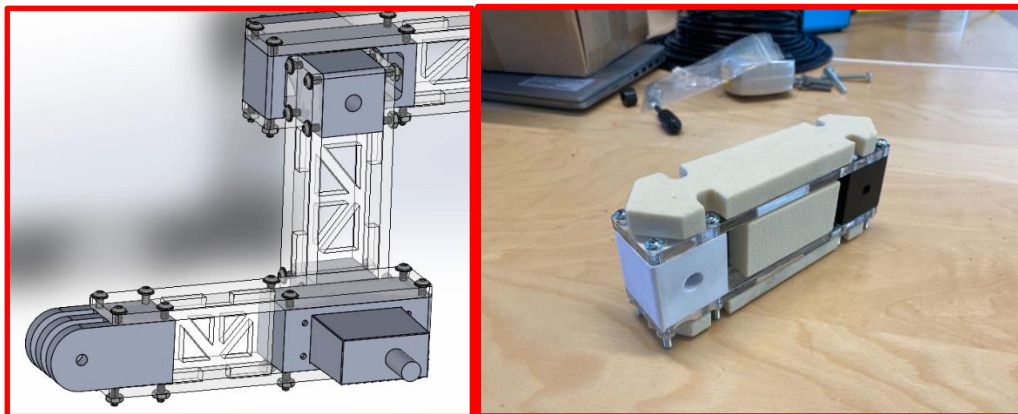


Figure 3.8: Arm CAD displaying designed negative space for foam; Arm link with subsea foam installed.

3.2.2 Claw

Table 3.3. Ranking claw design options based on requirements.

		Claw Design				
	Importance (weight)	Clam	Three Prong	Screw Jaw	Two Prong	Triangle Clam Scoop
Compatibility with Existing Tools	0.033	4	4	2	1	1
Cost	0.05	2	4	4	4	4
Manufacturability	0.117	2	1	3	2	3
Manipulation Ability	0.167	2	4	1	1	2
Range of motion	0.117	2	2	1	1	2
Weight	0.1	2	2	2	2	2
Size	0.1	2	3	3	1	2
Can collect rocks	0.133	3	2	1	2	3
Ability to break off thin rock layers	0.05	1	2	2	2	2
Manueverability/ Ease of use	0.133	3	2	1	1	4
Total Weighted Score		2.282	2.483	1.767	1.55	2.583

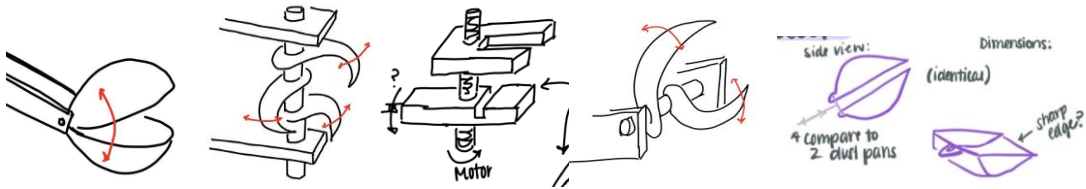


Figure 3.9: Clam, Three Prong, Screw Jaw, Two Prong, Triangle Clam Scoop (Respectively).

In the case of the claw, the triangular scoop design was the most promising option given its versatility and ability to collect different types of sediment more easily, including small rocks and sandy slush. This is seen in our final CAD design in Figures 3.10 and 3.11.

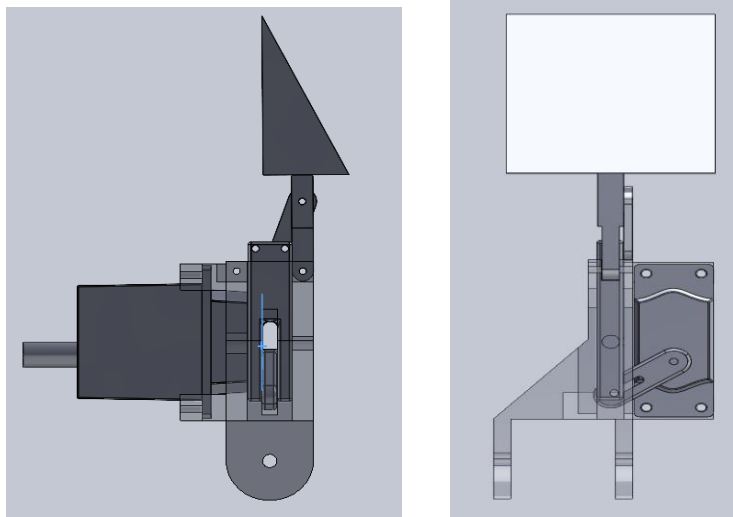


Figure 3.10 & 3.11. Chosen claw design (“Triangle Clam Scoop”).

3.2.3 Sample Storage

For the sample storage system, we followed a similar design process to the arm and claw, going from existing designs used for inspiration to concept sketches during the matrix phase—ranking the designs to one another depending on their ability to meet our customer's requests and other requirements best (Figures 3.12, 3.13, 3.14).

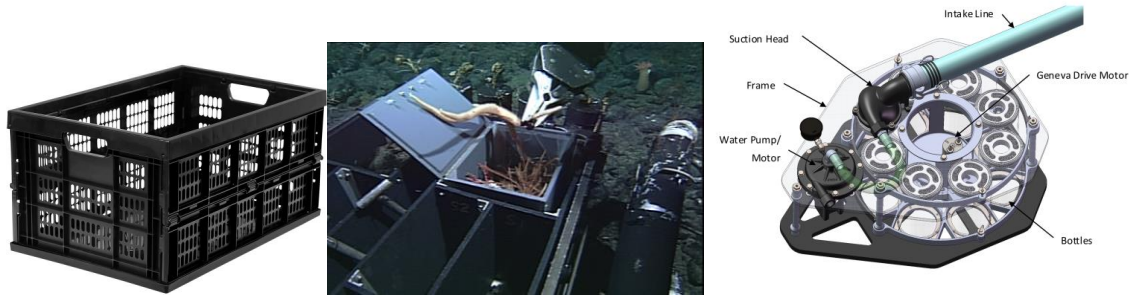


Figure 3.12: Existing designs used for inspiration.

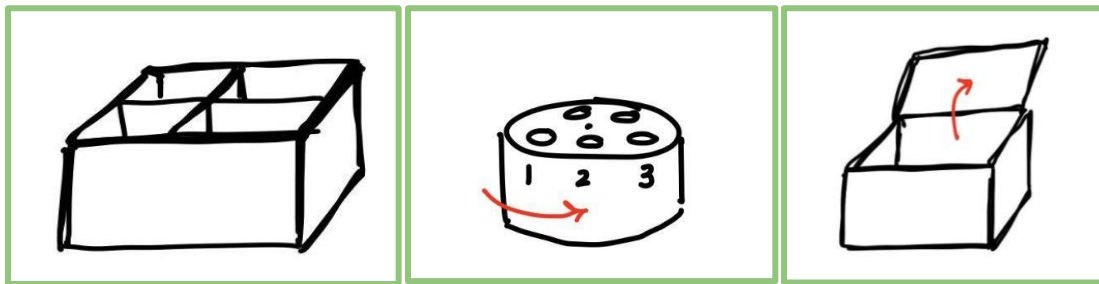


Figure 3.13 Concept Sketches from left to right (milk carton, rotating indicator, drawer).

Table 3.4: Ranking sampler storage design options based on requirements.

	Sampler Storage			
	Importance (weight)	Milk Carton	Rotating Indicator	Drawer
Compatibility with Existing Sample Takers	0.1	2	3	3
Size	0.08	1	3	2
Ease of use	0.14	2	3	1
Manufacturability	0.16	1	3	2
Storage Capacity (3-4 Samples)	0.04	1	3	2
Weight	0.12	2	3	1
Cost	0.08	1	3	2
Ability to index samples	0.16	1	4	1
Autonomy	0.12	2	3	1
Total Weighted Score		1.28	2.86	1.26

The rotating indicator, cylindrical sample storage container, proved the best option and rated the highest in our design matrix. Despite its more challenging manufacturing, this design was chosen because of its ability to index samples and keep them independent with one final endpoint for the claw to reach. This makes coding and use of the arm significantly simpler by simplifying the maneuvers required of the manipulator. In addition, it minimizes the shifting of weight, which would be an issue with an extending drawer setup. The final design decision (rotating indicator) is seen in CAD in Figure 3.14, and the manufactured subsystem is seen in Figure 3.14.

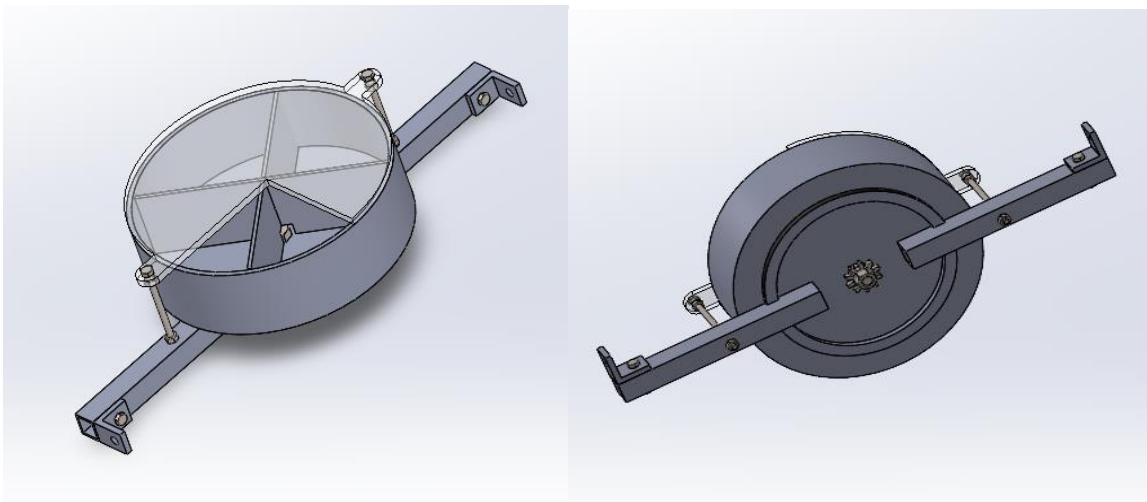


Figure 3.14: CAD of decided on sample storage design concept.

To fit into our budget, we tried to use less expensive servos for any components that do not need as much torque. However, these servos are limited to 148 degrees rotation. To achieve a 360 spin, we needed to incorporate a gear ratio of at least 2.5 (see calculations in Figure 3.15). The dimensions of the servo limit it from being able to sit directly under the storage pan that it needs to spin. Adding gears and a belt also makes it possible to move the servo elsewhere in the frame. Figure 3.16 shows the part designed and 3-D printed to hold the servo elsewhere in the frame.

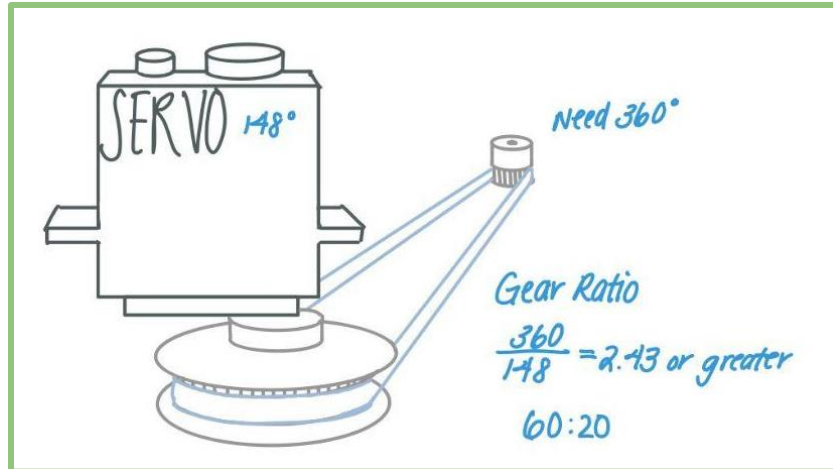


Figure 3.15: Gear ratio visual and calculation.

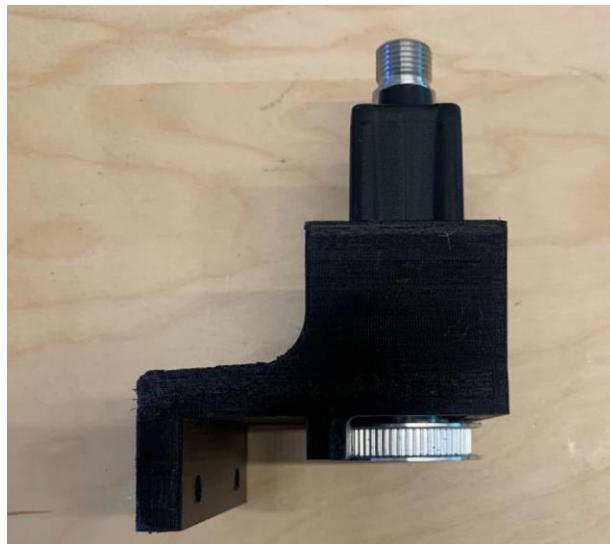


Figure 3.16: Sample storage system servo fixture to secure servo and big gear to ROV frame.

A higher ratio means higher driver speed is needed to make the pan spin at its original rate. However, the servo can still run fast enough with the gear decrease, taking about 2 (1.87) seconds to accelerate to its .12s/60 deg maximum servo speed. This is plenty fast for something that we do not even need to move so quickly in the first place. Also, checking with the load estimation and this gear ratio of 2.5, the cake tin full of three max-sized samples and water (about 12.5lbs) can still get up to speed above water for easy sample removal without removing the whole apparatus from the frame. Calculations for this can be found in Appendix D. It is also

important to note that the gear ratio used was three because it is much easier to order.

When it came to manufacturing, we wanted to use scrap parts and keep them durable as it sits on the bottom of the robot. We also wanted to purchase any parts that were hard to make on campus. These things presented their challenges, incorporating not only 3-D printing but the machining and laser cutting. Figure 3.17 shows machined Delrin plastic parts in red, laser-cut acrylic parts in green, and drilled or cut pre-purchased aluminum parts in black, while the purchased aluminum hardware is in gray. More details on manufacturing can be found in Section 4.

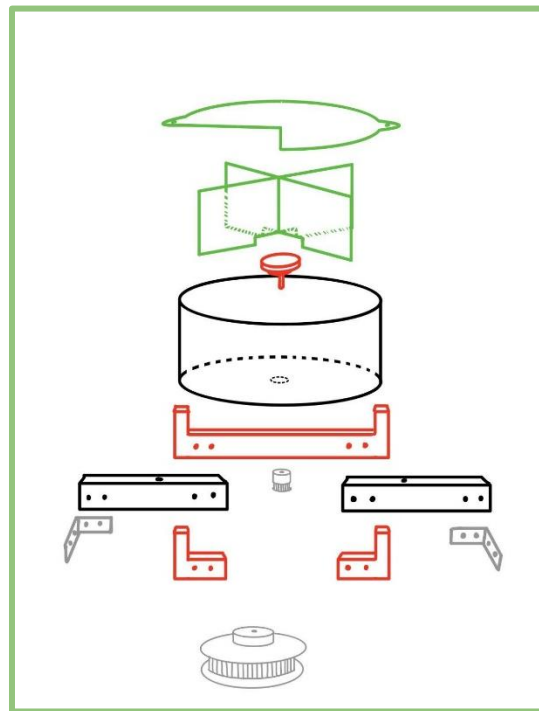


Figure 3.17: Sketch of sample storage system final design.

Figure 3.17 is the storage system at the end of this quarter. It experiences some operational challenges and has much potential for improvement. For example, if the gears are too small and without a bearing, the servo pulls the pan towards it rather than spinning it. A thrust bearing has been purchased, and more giant diameter gears to mitigate this. More on future work can be found in Section 8.



Figure 3.18: Sample Storage System assembled at end of the quarter (from below the robot and before installation).

3.2.4 Electronics Tube

To keep the sample retrieval system, separate and removable from the rest of the ROV system, a separate waterproof tube was needed to contain an additional battery and the controls. We purchased a 4" diameter acrylic tube from Blue Trail Robotics and located it in the stern to minimize obstructions (Figure 3.19). This additional tube added buoyancy, disbalancing the robot. However, the last team to work on Nautilus integrated a modular dive weight system to the robots in eight different locations that could be utilized to mitigate this.



Figure 3.19: Blue Trail Robotics Waterproof Tube.

To attach this tube to the robot, we used a simple hose fitting and machined two aluminum slips to screw onto the frame, seen in Figure 3.20. These parts were found in the machine shop scrap, required little manufacturing, and made for the tube to be easy to remove.



Figure 3.20: Additional controls tube attachment to main ROV frame.

3.3 Electronics

3.3.1 Existing Work

When we took over the Nautilus project, it was already a mission capable ROV that had an extensive and versatile set of electronic components. The main onboard control unit was an Arduino Mega 2560, shown in in figure 3.21, which has 50 digital inputs and 15 analog inputs with support for I²C and RS485 communication protocols. There were also six sensors that took up many of these ports – the Blue Robotics Bar30 pressure sensor, Blue Robotics Celsius temperature sensor, Adafruit LSM303 IMU, Blue Robotics ping solar altimeter and echosounder, Blue Robotics leak sensor, and Adafruit power sensor – which are shown in Figure 3.21. Three lithium-ion batteries are used to power the ROV and there is a power switch, DC-DC buck converter, and 200A fuse inside the ROV to regulate power. A serial bus exists to connect all the sensors to the Arduino for bilateral communication.

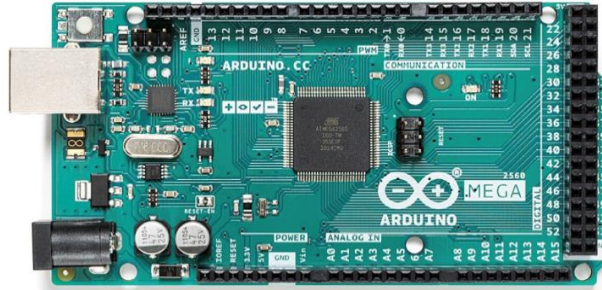


Figure 3.21: Arduino Mega 2560 Rev3.

A Raspberry Pi and camera also operate via a Fathom Interface Board over ethernet to have a live video feed to the topside user. A full electrical wiring diagram of the electronics system we inherited is shown in Figure 3.23.

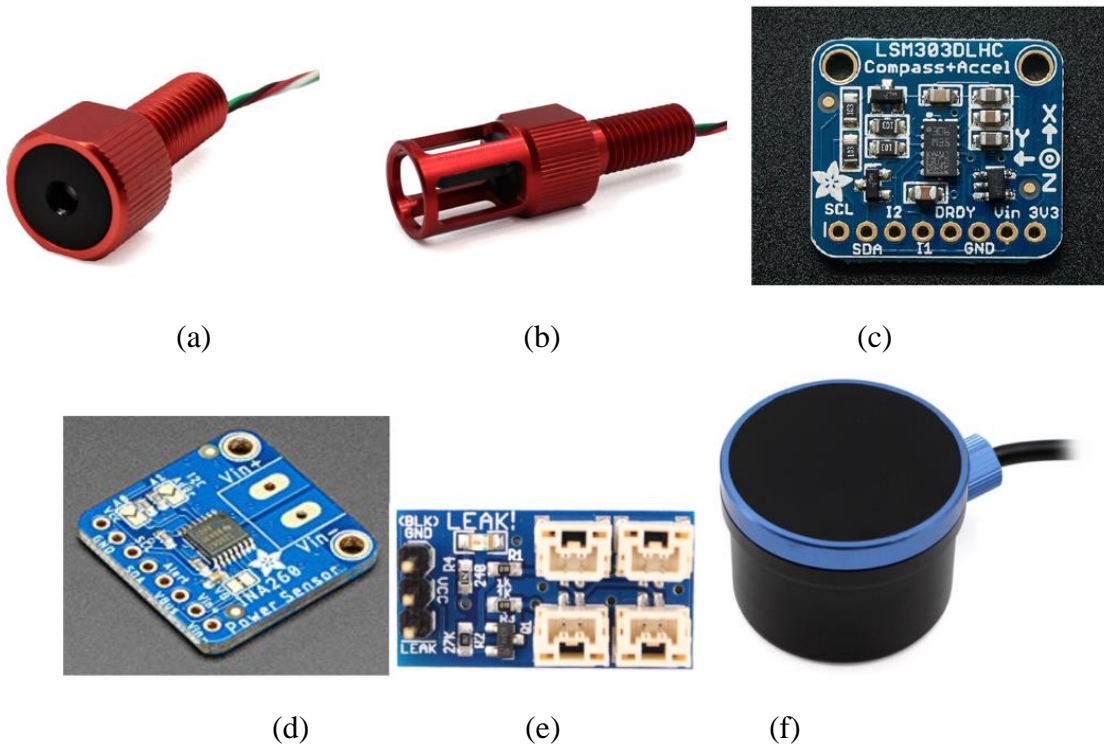


Figure 3.22: Blue Robotics Bar30 pressure sensor (a), Blue Robotics Celsius temperature sensor (b), Adafruit LSM303 IMU (c), Blue Robotics ping solar altimeter and echosounder (d), Blue Robotics leak sensor (e), and Adafruit power sensor (f).

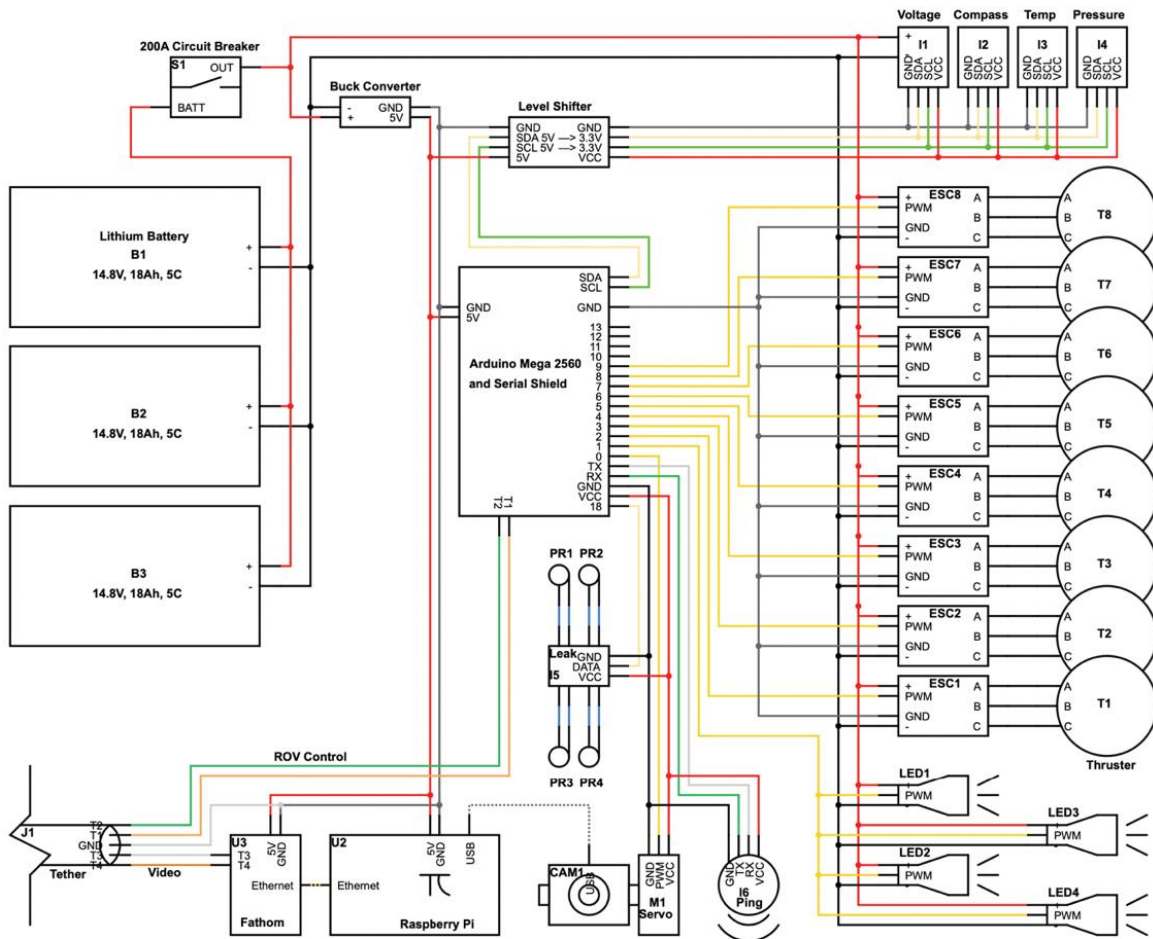


Figure 3.23: Existing Electrical Components Wiring Diagram.

3.3.2 Requirements Gathering & Design Process

After identifying these subsystems, we narrowed down the electrical and software layouts we would need. Having an electrical foundation already established meant there was something we could build upon. This also limited our design options since we had to work within the constraints of the current system settings. The team identified that we would need to add servos for the different mechanisms we are building that are programmable for their respective functions. The individual wiring and any subsequent electronic components must also be incorporated. For example, specific servos within the arm should rotate in certain directions, and the storage mechanism servo should move a set number of degrees to reveal each storage slot. The preliminary wiring diagram in Figure 3.24 shows our attempt to address the issue of adding

additional servos to the existing Nautilus control module with limited Pulse Width Modulation (PWM) ports. This design would make it difficult to scale if we wanted to add more degrees of freedom to the arm or give it additional functionality.

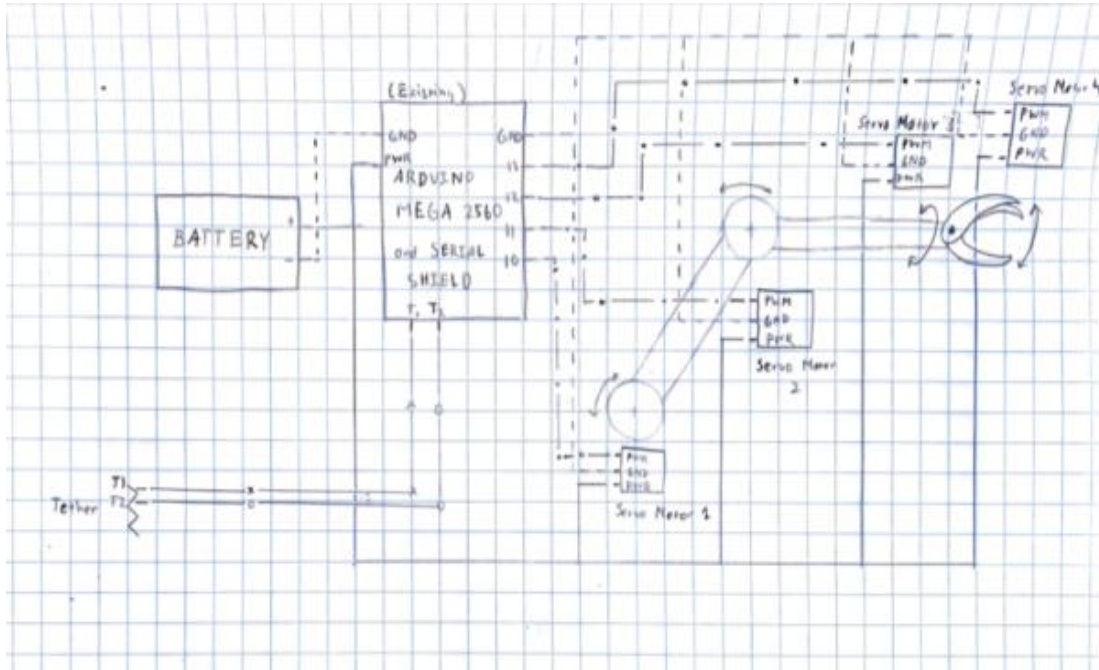


Figure 3.24: Initial Electrical Wiring Diagram.

The existing Arduino Mega 2560 also had limited remaining ports. Many are being used by the sensors already installed on the Nautilus ROV. The servos we ordered came with connected PWM headers, so we had to use ports compatible with them. We could either create an arm with less servos therefore minimizing the degrees of freedom or figure out another way to integrate another board onto the Nautilus ROV.

After completing our due diligence on the existing system, we discovered that the existing sensors were being controlled via the Inter-Integrated Circuit (I²C) protocol with 3.3 logic on the serial bus already installed. I²C is a bus interface connection protocol meant for short-distance serial communication. This means the distance between the devices on the shared bus cannot be too long, or the packet loss rate becomes too high. The length is usually capped at about one meter. It uses two bi-directional data lines, Serial Data (SDA) and Serial Clock (SLC), to communicate with all devices on the bus. Figure 3.25 depicts a visual representation of the I²C protocol and how devices are connected to the shared bus. There are two types of devices - a

particular controller device and up to 128 slave devices. A multi-master setup can be configured if needed. The master device controls and manages data sent across the bus to the different slave devices.

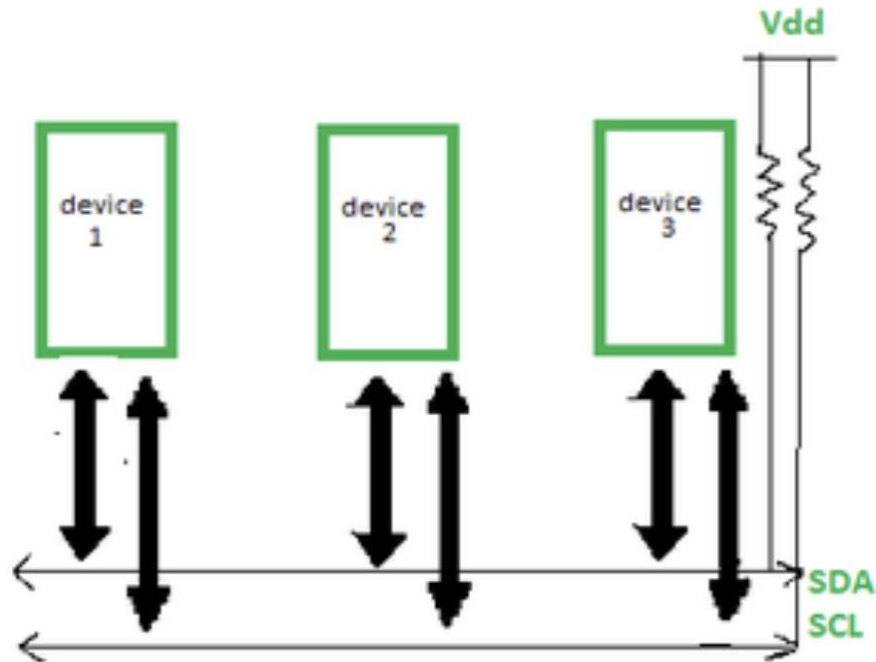


Figure 3.25: Representation of the I²C Protocol [22].

The master device manages the SDA and SCL and the packet queue. We only have one slave device for our system, but if a future group wants to add more devices for other appendages, they can. The modularity and scalability of electronics significantly increase with I²C. There are many benefits to this decision. We would not need to wire all the arm or storage mechanism servos back into the original electronics housing. We could also install a secondary housing dedicated to the appendages' electronics, reducing wiring complexity and promoting modularity. There would be minimum wiring additions needed to be done to the existing system, and it would mitigate any wire length limitations.

3.3.3 Final Design & Wiring

Our final electronics design is to have an Adafruit 16-Channel Servo Driver microcontroller dedicated to managing our arm servos. It is communicated by the existing

Arduino Mega 2560 via I²C, as shown in Figure 3.26. Four I²C bus connections will be the only physical connections to the main Nautilus control module. Utilizing the microcontroller is beneficial for multiple reasons. We can set up the arm to be both modular and scalable for the future. Since it has more available pins, sensors or additional servos can be connected to it for control. It also reduces the processing complexity on the Arduino since the packet addressing and forwarding to individual servos is done at the microcontroller.

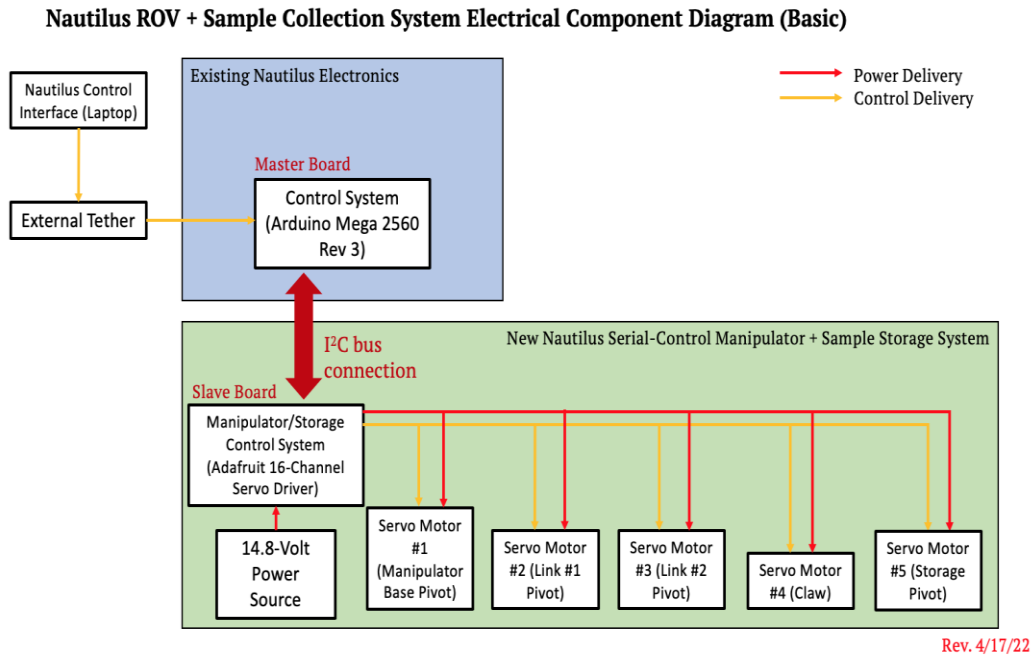


Figure 3.26: Basic Electrical Component Diagram.

Figure 3.27 is a diagram which depicts the low-level wiring. The red-highlighted area is the existing Nautilus electronics system that was already in place when we took over the project and the green-highlighted area is what we added. As you can see, many servos and sensors were already connected to the Arduino Mega. The data comes from a singular entry point - the tether - and is fed through the primary control system's Arduino. The data is then sent to the I²C bus and is sent to the microcontroller. We used a step-down transformer with our 14.8V battery to ensure a proper voltage of 4.8V is supplied to the microcontroller. Now, the packet will be processed and sent to the respective servo at the microcontroller it was addressed to. For example, if one wanted to move the storage mechanism, the command would follow the data flow to the

microcontroller. It would then be mapped and delivered to the storage mechanism's servo where it will be executed there.

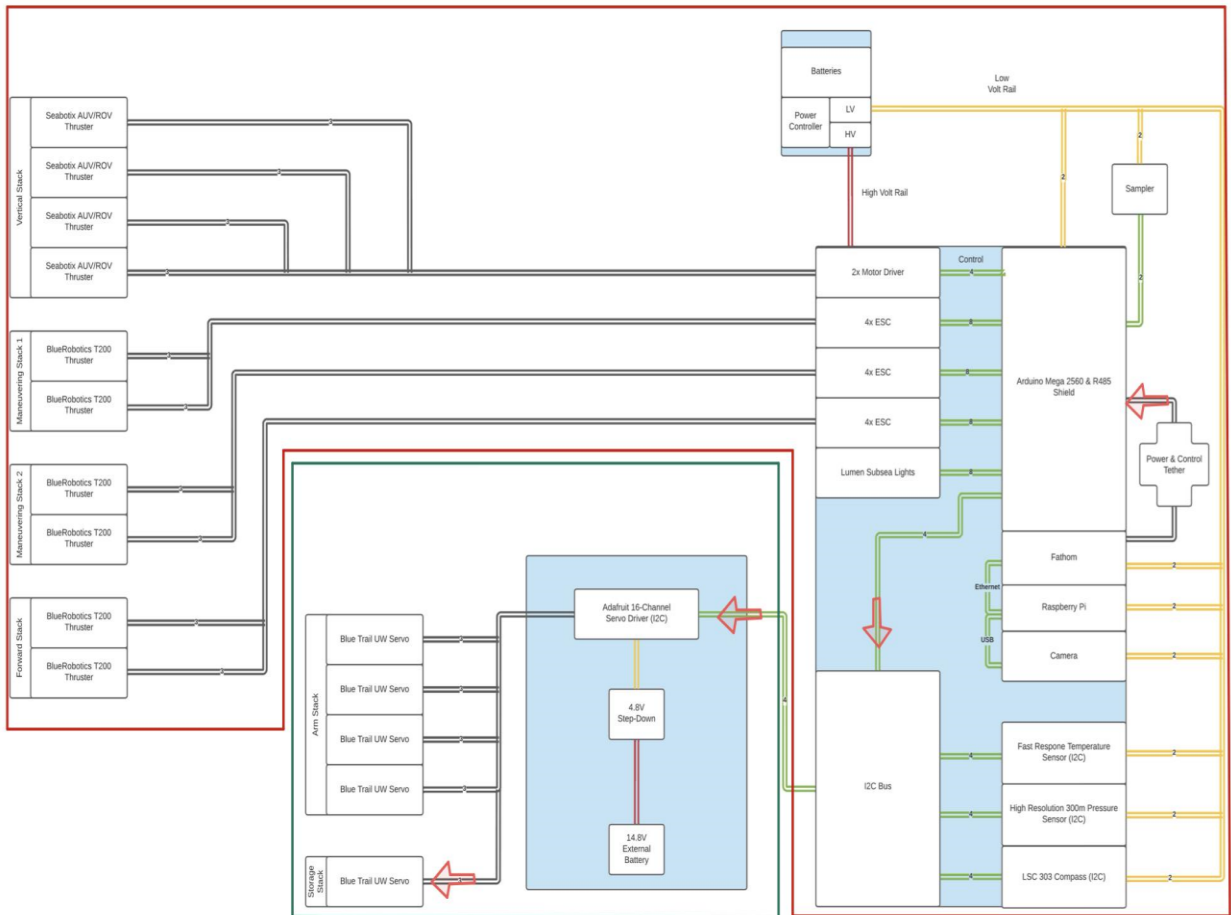


Figure 3.27: Final Wiring Diagram.

3.3.4 Control Methodology/Control System

The Nautilus initially had a single Xbox style controller that controlled movement and auxiliaries on the ROV. This controller was connected via USB to the top-side laptop. It already took both hands and full attention of the pilot to just maneuver to ROV, so we added a second Xbox controller that is dedicated to the arm attachment. This allows one pilot to focus on moving the ROV while one pilot focuses on operating the arm. In order to do this, we used a USB hub to that the controllers were connected to for interfacing with the top-side laptop. For the sake of time, we chose to implement individual servo control instead of endpoint control. This allows a high degree of control and freedom, but it can be challenging to learn how to operate.

3.4 Software

3.4.1 Existing Work

The previous team provided a functional ROV control system with a top-side GUI and subsea Arduino microcontroller via the RS485 communication protocol, which is reliable over long distances. The GUI, shown in Figure 3.28, has three graphs that display the changes in altitude, depth, and heading over time and has buttons to lock the ROV at certain values. It also

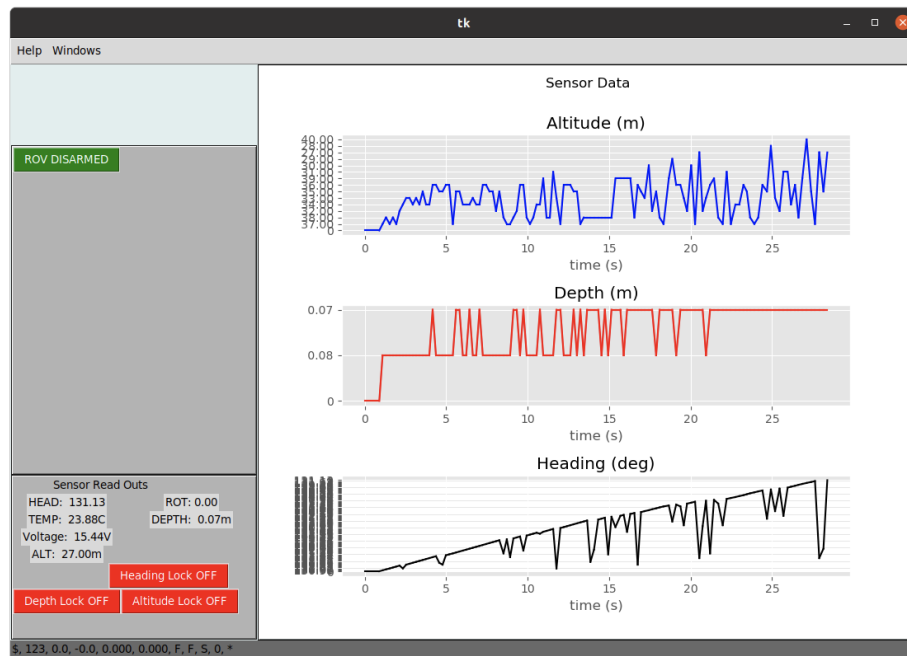


Figure 3.28: ROV GUI.

displays the sensor read-outs and has a window to enter values to make the closed loop control tuning much simpler. A separate window with live video stream of the subsea camera also is provided with the GUI. The ROS (Robot Operating System) handles communication between the GUI and subsea control system. The ROS is a set of libraries and packages that provide functionality for robotic systems. The NMEA (National Marine Electronic Association) string protocol is the data transmission standard the ROS parses. These commands must be formatted properly by whichever control system produces them before being encapsulated by packets and sent via the tether. The ROV subsea control system and GUI produce different NMEA strings

because the contents sent from one to another are different. The GUI is sending thruster values and commands while the subsea control system is sending sensor read-outs. The existing software also came with data logs so a scientist can view the sensor readings at a specific time in parallel with the video footage that was taken.

3.4.2 Requirements Gathering & Design Process

In order to have an operating sample retrieving system, we needed to add three key functionalities to the existing software – rotating the storage system, maneuvering the arm, and controlling the claw. From an integrated systems perspective, we needed to work within out limitations of the electrical layout while focusing on modifying our system without adding high latency or overhead. We also wanted our system to be modular, which would allow for the ROV to operate with or without the sample retrieval system. Our original plan was to make a secondary software loop to control our system separately from the main ROV control system as seen in Figure 3.29. This would ensure a higher level of modularity and not having to change and possibly rework parts of the original control loop. It also allowed for a much higher level of modularity. However, this complicates the wiring and electrical components a great deal more. We would need to add another Arduino board onto the ROV and interface with it. Although this may not be difficult to implement, there would be a great deal more latency due to the added processing requirements on the main Arduino board. Since the servo positioning calculations would be done on the Arduino, it would have to re-encapsulate every command to send to the second loop board and wait for it to be unpackaged and forwarded to the correct servo. Based on our requirements gathering, we did not want even a single extra millisecond of delay that could inhibit a pilot from operating the arm effectively and retrieve a sample. As seen in Figure 3.30, our final design was to integrate the controls directly into the main loop. We were able to do this by connecting a microcontroller splitter to the I²C serial bus connection, allowing easy servo control and minimal physical connections. This made it easy to connect our servo controller to the ROV since we only had to plug one port into the bus. Since I²C devices need a unique address for the Arduino to know which device to send data to, we had to change the default address for our servo controller since it coincided with the voltage sensor's address.

To reduce the amount of code and processing needed on the Arduino, we do all the arm servo calculations on the topside computer and simply add the values to the packet sent downstream through the tether. Then, on the bottom side, the Arduino simply sends the pre-calculated value directly to the servos through the servo controller. This keeps the code lightweight and responsive for the arm. This was only able to be done this efficiently using our final design since the microcontroller acts as a gateway to the servos connected to it so we can address directly to them instead of having to send it to another board first. It may be less modular, but the code on the bottom side is only a few lines per servo and the reduction in cost is greatly worth it.

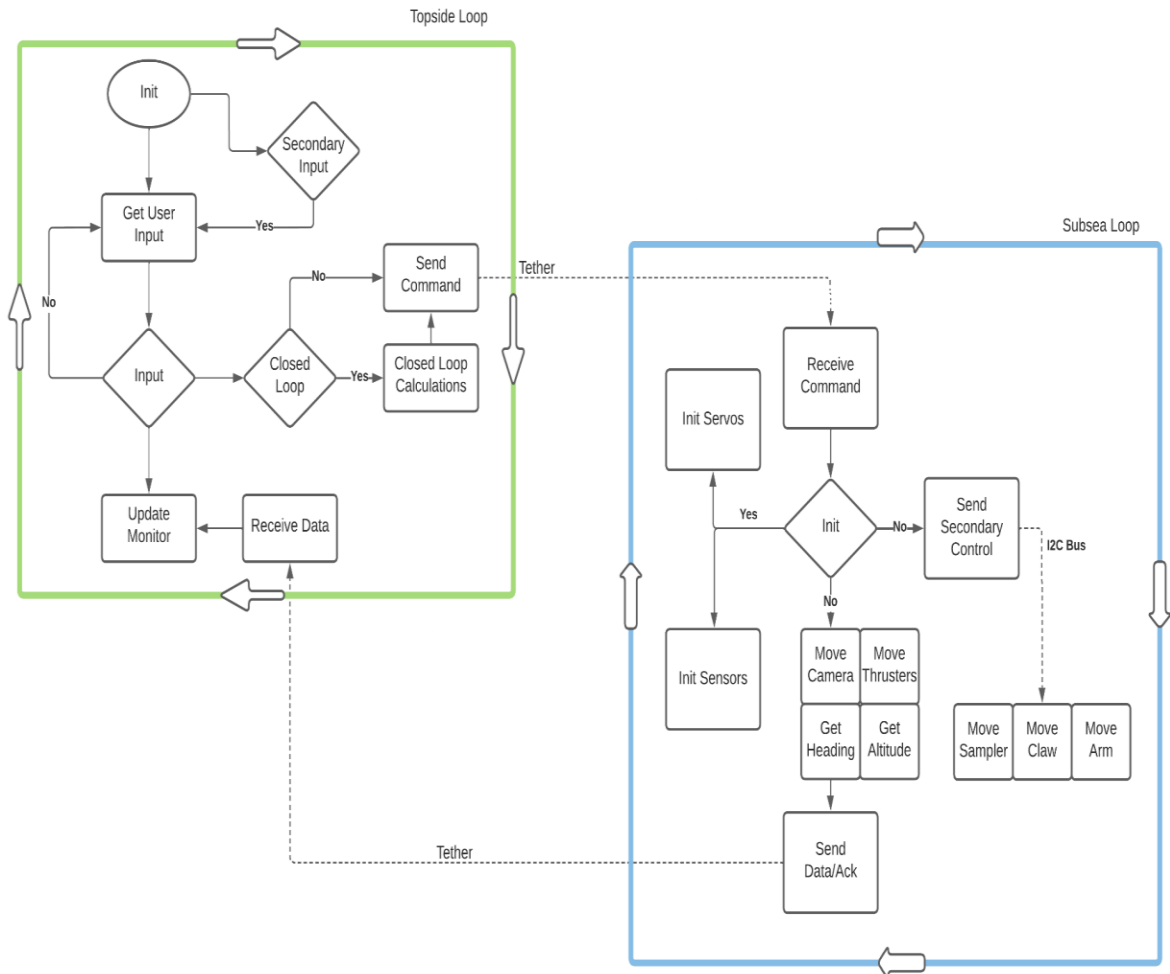


Figure 3.30: Final Software Diagram

3.4.3 NMEA Communication Strings

Communication strings were already being used to communicate both from the topside to subsea and subsea to topside. All this communication happened via the tether and everything from thruster values to sensor data was communicated in these strings. As mentioned earlier, we continued to add upon the NMEA transmission standard the strings were formatted in. The benefit of our software design is no data is transmitted from the arm subcomponent back up to the topside. This is because there is no data the arm collects or acknowledgement packets needed to be sent. We can adjust the arm based on the live video feedback we are receiving and even if there is some packet loss during transmission, it is minimal and can be corrected with further small adjustments. The tether and communication protocols we use are very reliable for the distances we use them across, so any consideration of packet loss was minute compared to the considerable overhead we saved. Because the arm does not send any data, we did not have to change the subsea to topside string at all. However, we did have to considerably alter the topside to subsea string since we were now sending five additional servo values and their end addresses. The strings are broken into subcomponents called tokens. Each token is a value for the ROS to parse and properly deliver to its respective end recipient. The subsea to topside string has 8 tokens and the topside to subsea string has 15 tokens. Below is a breakdown of both strings, the tokens they contain, and what each token value is for.

Topside to Subsea String

Token 0: Message Start

The “\$” character is the start of any command message. This helps the GUI differentiate between where the start and end of the different messages it receives are. It also helps prevent and detect packet loss.

Token 1: Message ID

The message ID is used to distinguish packets from one another when parsing data logs. It helps keep track of which messages were sent during a certain time interval and group data from the various sensors.

Token 2: Forward/Backwards

This token is the vertical axis of the first controller's left joystick mapped to a -1 to 1 range with -1 being all the way down and 1 being all the way up. Going full speed backward is represented by -1 and full speed forward by 1.

Token 3: Translate Left/Right

This token is the horizontal axis of the first controller's left joystick mapped to a -1 to 1 range with -1 being all the way left and 1 being all the way right. Going full speed to the left is represented by -1 and full speed to the right by 1.

Token 4: Vertical Up/Down

This token is the first controller's left trigger of the controller mapped to half of the range, 0 to -1, with 0 being unpressed and -1 being pressed all the way down. The right trigger of the first controller maps to the other half of the range, 0 to 1, with 0 being unpressed and 1 being pressed all the way down. Descending at full speed to the left is represented by -1 and ascending at full speed to the right by 1.

Token 5: Rotation

This token is the horizontal axis of the first controller's right joystick mapped to a -1 to 1 range with -1 being all the way left and 1 being all the way right. Rotating full speed to the counterclockwise is represented by -1 and rotating full speed to the clockwise by 1.

Token 6: Light Toggle

This token is toggled between T and F every time the triangle button on the first controller is pressed. By default, it is set to F.

Token 7: Sampler Toggle

This token is toggled between T and F every time the square button on the first controller is pressed. By default, it is set to F. Currently, this value is interpreted but not used by the Arduino.

Token 8: Camera Tilt

This token is toggled between U, D, and S. While ‘up’ on the first controller directional pad is pressed, token 8 is U, tilting the camera up. While ‘down’ on the controller directional pad is pressed, token 8 is D, tilting the camera down. When neither are being pressed, token 8 is S, not tilting the camera.

Token 9: Closed Loop

This token is toggled between T and F every time the closed loop control button is pressed on the GUI. By default, it is set to F.

Token 10: First Arm Link Servo

This token is the horizontal axis of the second controller’s left joystick mapped to a -1 to 1 range with -1 being all the way left and 1 being all the way right. The first link moving to the left is represented by -1, moving to the right by 1, and unmoving at 0. The acceleration speed is constant regardless of how deep the joystick is pushed.

Token 11: Second Arm Link Servo

This token is the vertical axis of the second controller’s left joystick mapped to a -1 to 1 range with -1 being all the way down and 1 being all the way up. The second link moving downwards is represented by -1, moving upwards by 1, and unmoving at 0. The acceleration speed is constant regardless of how deep the joystick is pushed.

Token 12: Third Arm Link Servo

This token is the vertical axis of the second controller’s right joystick mapped to a -1 to 1 range with -1 being all the way down and 1 being all the way up. The third link moving downwards is represented by -1, moving upwards by 1, and unmoving at 0. The acceleration speed is constant regardless of how deep the joystick is pushed.

Token 13: Claw Servo

This token is the second controller's left trigger of the controller mapped to half of the range, 0 to -1, with 0 being unpressed and -1 being pressed all the way down. The right trigger of the second controller maps to the other half of the range, 0 to 1, with 0 being unpressed and 1 being pressed all the way down. The claw closing is represented by -1 and opening by 1. The acceleration speed is constant regardless of how long the triggers are pushed.

Token 14: Storage System Servo

This token is the second controller's X button of the controller mapped to half of the range, 0 to -1, with 0 being unpressed and -1 being pressed all the way down. The right B button of the second controller maps to the other half of the range, 0 to 1, with 0 being unpressed and 1 being pressed all the way down. The storage system rotating left is represented by -1 and rotating right by 1. The acceleration speed is constant regardless of how long the buttons are pushed.

Token 15: End of Message

This token contains the end of message character, '*'. This lets the GUI know when the message ends and to finish parsing the current message.

Subsea to Topside String

Token 0: Message Start

The "\$" character is the start of any command message. This helps the GUI differentiate between where the start and end of the different messages it receives are. It also helps prevent and detect packet loss.

Token 1: Message ID

The message ID is used to distinguish packets from one another when parsing data logs. It helps keep track of which messages were sent during a certain time interval and group data from the various sensors.

Token 2: Temperature

The temperature reading is a float with two digits of precision and a range between -40 to 125 Celsius.

Token 3: Depth

The depth value is a float value with 2 digits of precision provided by the pressure sensor. The depth is provided by a method from the pressure sensor library that converts the normal pressure value to a depth value.

Token 4: Heading

The heading is a float value with 2 digits of precision. The value ranges between 0 to 360 degrees.

Token 5: Altitude

The altitude is a float value with 2 digits of precision. The value is provided by the ping sensor which outputs distance in millimeters which is then converted to meters.

Token 6: Leak

The leak token is an integer value that is either 0 if there is no leak or 1 if there is a leak.

Token 7: Voltage

The voltage is a float value with 2 digits of precision. The value is provided by the power sensor and supports a range of 0 to 36 volts.

Token 8: End of Message

This token contains the end of message character, '*'. This lets the GUI know when the message ends and to finish parsing the current message.

3.4.4 Manipulator Kinematics for Servo Calculations

Our manipulator design is a serial chain manipulator with three different joints, each controlled by a servo motor. The rotation of these servo motors controls the entirety of the

manipulator's motion. Therefore, we sought to study and understand how the rotation of each joint converts to translational movement of the claw position in an XYZ coordinate plane using standard rules set by Denavit-Hartenberg for serial chain manipulators. In Figure 3.31, we assigned an XYZ coordinate axis to the workspace of our manipulator and relative coordinate axes to each joint of our arm and the end effector - the point at the tip of the claw. This is the point where the samples are collected. This coordinate system was set following the guidelines that the z-axis must be the axis of rotation. In addition, the x-axis must be perpendicular to the current and previous z-axis.

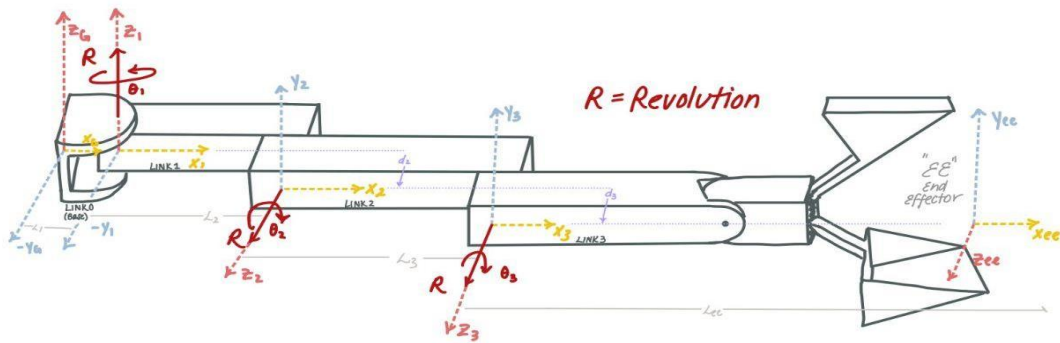


Figure 3.31: Diagram of the Manipulator with coordinate axes and rotational axes pointed out at each joint and the end effector.

Rotational matrices for the arm motion are created using the Denavit-Hartenberg Parameters shown in Table 3.5. The link length (a) is the fixed length between joints. The link twist angle (α) is the angle between rotation axes from one joint to the next. The link offset (d) for each joint is the distance along the axis of rotation between where one link sits and the next rotary. Finally, the joint angle (θ) is the rotation angle between the successive relative joint axes. We could construct a homogeneous transformation matrix and a Jacobian matrix using these values. The generalized transform matrices and equations for transforming translational movement of an end effector to rotational values of connected joints can be seen on the next page, Eqn. 1 Eqn 2 and Eqn 3. Through the Jacobian matrix and its inverse, we would be able to translate the rotational velocity of each joint to the translational movement of the arm in an XYZ coordinate system. Implementing this kinematic analysis was not a part of our design

requirements, however, our understanding of this can lead to software and control improvements in the future.

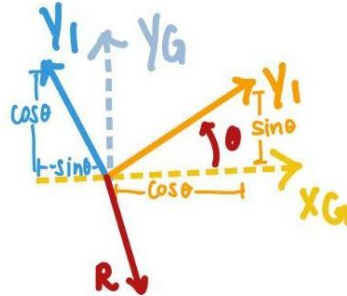


Figure 3.32: Sketch showing transform from global to first joint axis.

$${}^G T_1 = [({}^G \hat{X})({}^G \hat{Y})] \quad \text{Eqn. 1}$$

$${}^G T_1 = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \quad \text{Eqn. 2}$$

$${}^G T_1 {}^1 T_2 {}^2 T_3 {}^3 T_{ee} = {}^G T_{ee} \quad \text{Eqn. 3}$$

Table 3.5: Denavit-Hartenberg Parameters for Nautilus Manipulator with variable joint angles.

Link Length: a	Link Twist: α	Link Offset: d	Joint Angle: θ
L1= 3"	0	0	θ_1
L2= 7 3/16"	-90	1.5"	θ_2
L3= 5 1/16"	0	1.5"	θ_3
EE= 13 7/8"	0	0	θ_{ee}

Section 4: Manufacturing

Although we did our designs with manufacturing options in mind, there were still a plethora of things to consider when it came down to building each part. In addition, parts that we could purchase still had to be adjusted to be compatible. Once we had designs and drawings and their necessary material traits, we had to finish figuring out the best ways to make them come to life. We used a mix of manufacturing types for the whole system to come to life, including 3-D printing, laser cutting, and machining.

4.1 Maker Lab

The Sobrato Campus for Discovery and Innovation (SCDI), which was opened last year, included a new Maker Space! This space includes light fabrication tools like handheld drills and saws and 3-D printers and laser cutters. After completing basic training and a couple more specialized pieces of training in person and online, we had more than half our team trained and given permission to use the space. This was vital for our plastic components and made it possible to reiterate parts as designs changed.

4.1.1 3-D Printing

One of the main tools we used was the Prusa i3 MK3S+ 3D Printers provided by the MakerSpace and the resources provided by the Mechanical Engineering Department in The Garage. These printers are very powerful for their price, and thus the University has about twenty that we have access to. We only used a small number of their capabilities to print PETG and ABS within similar print parameters within our project, but their capabilities reach far beyond this. For example, the layering parameter alone could change printed performance drastically, ranging from 0.05mm layers to .35mm layers.

Our environment highly drove our choice of material to print in. Unfortunately, the marine environment is highly corrosive to many plastics and can ultimately cause leaching of micro or loss of plastics. We have decided to use PETG and ABS to prevent this as they have much more durable structures and will not shed and degrade. Instead, they will become worn and eventually break. If we replace parts consistently, this should not happen, and we will not add pollution to the oceans.

Based on what 3D printing allows us to do in a design framework is incredible and cannot be replicated with machining often. It is exorbitantly expensive to do through casting. Thus, it is often a necessary evil in small productions. Though it allows us to do very intricate things quickly and reliably, there are other drawbacks, such as printer errors that require prints to restart or wrong print settings that change the tolerances of the prints and make them not fit and require adjustments. This meant our timeline got drawn out further than expected, as we had to reprint parts and sand not only the 3D Prints but the Servos to make everything together.

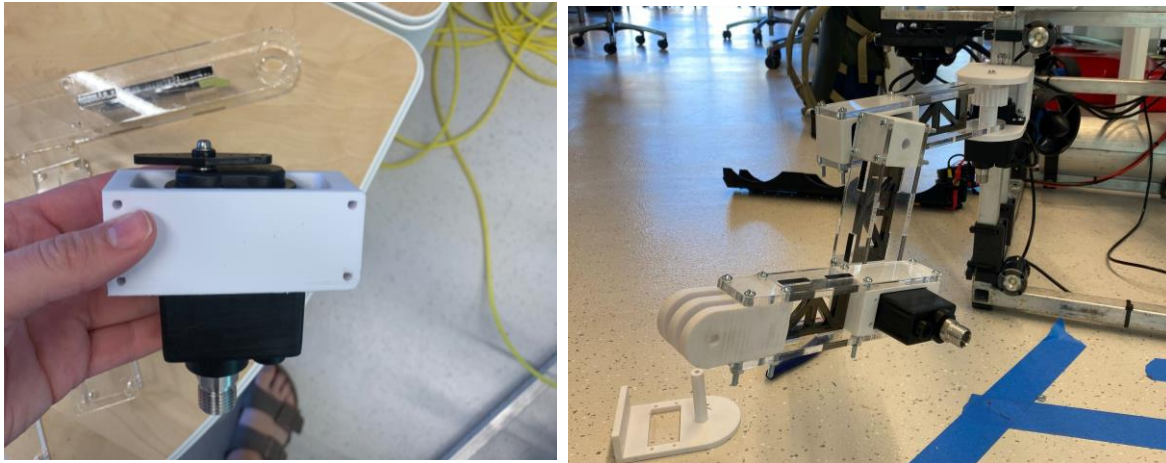


Figure 4.1: 3-D printed servo fixtures and arm components

4.1.2 Laser Cutting

The MakerSpace on campus has Prusa printers and Epilog laser cutters capable of cutting acrylic sheets up to a quarter-inch thick. Acrylic was an essential material for our design; its density is close to that of water, making it essentially "weightless" when used underwater. This was important, especially in the arm design since the servo closest to the frame will have to endure much force. It was also convenient for dividers and a lid on the storage system, coming in flat sheets and easy to iterate/ make if broken. The maker lab also does an excellent job of keeping acrylic scraps that we maximized our use of. This was both good for our budget but also an environmentally conscious decision.

To make the I-beam arm sections and lid and dividers for the storage system, we first completed laser cutter training, consisting of a quick one-hour lesson. After this, we downloaded our Solidworks drawings as STLs, set the acrylic cutter settings, and quickly cut out the

necessary parts. There were some challenges with iterating the settings of the laser to make sure it did not melt the part off.

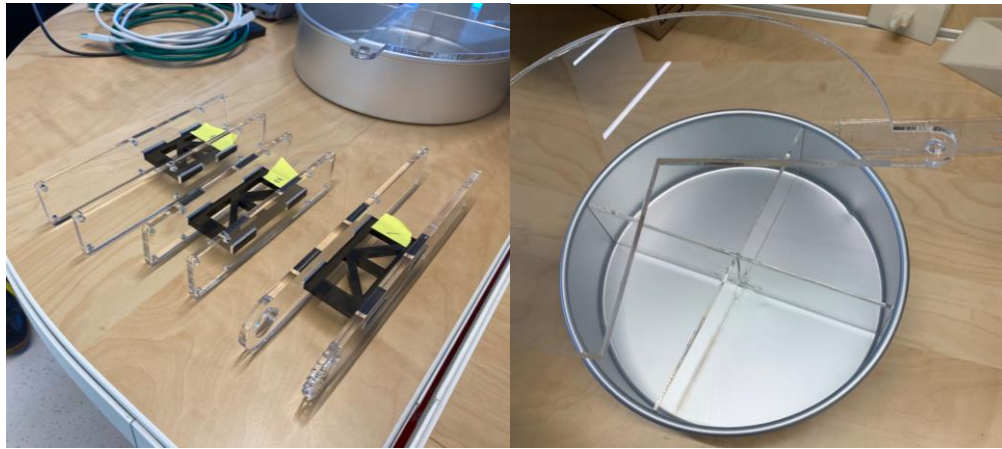


Figure 4.2: Laser cut components of arm and sample storage

4.2 Machine Shop

We had access to a Maker Space, but we also had access to the machine shop in SCDI after completing a Mech 101 course, “Prototype Manufacturing and Machining Lab/ Light Fabrication Training.” This machine shop gave us access to saws, lathes, and mills and the ability to make a broader range of our parts on campus.

4.2.1 Machining

Machining is one of the most robust manufacturing techniques because it is a subtractive manufacturing method. This subtractive method allows grain structures to form better in the base material when compared to casting or forging, where grain structures in metal are compromised. Modern machines also offer more precision than any other manufacturing method, with readouts regularly within five ten thousandths of an inch on even primary machines. However, this precision is not easy to harness and requires experience and intelligent manufacturing. This often comes in the form of doing actions correctly to make sure all parts are appropriately indicated to each other.

Machining takes the best things from many different tools, mainly lathes, and mills, to create just about anything you can think of. Both use rotational motion to do work on a piece

through tools. This definition sounds roundabout and vague but encapsulates the creativity it takes to manufacture many complex parts. Within our university, we have a highly experienced machinist overseeing all of our projects which are very willing to provide his wisdom to us, which has been invaluable many times. The immense advantages of machining precision are often outweighed by its setup time and can be done simply by hand for non-driven dimensions on parts, such as the rounded sides of the servo horn below. This servo horn was machined with high precision for the slot, and the servo connector on the other side with minimal precision was used for the bevels. Parts on the storage system were also machined. From cutting and drilling into the aluminum, bar supports to the Delrin plastic supports and gear holder. These parts did not need super-precise tolerancing and were made from scraps around the machine lab. The tolerance was forgiving because we used extra nuts to adjust the distance of the Delrin supports to the pan, giving us more flexibility for the difficult-to-measure part.



Figure 4.3: Machines slots with hand sanded rounded corners.



Figure 4.4: Machined Delrin plastic parts for sample storage system

4.2.2 Fabrication and Assembly

Once all parts were printed, laser-cut, or machined, the final step in the manufacturing process was a light fabrication and general assembly. This included drilling holes in the frame, filling down any sharp edges, and screwing subsystems together and then to the frame. This light fabrication was a more extensive manufacturing section than expected due to tolerance issues in 3D printing and machining. Adjusting and changing parts after printing and machining allowed us to waste less material in redesigns. The arm itself does not drill into the frame but rather pinches the frame. However, the storage system has a corner bracket on either side of its aluminum bar supports and the other electronics tube; both require holes in the frame of the ROV itself.

Section 5: Testing

Our testing was broken down according to our different subsystems, with each intended to prove individual capabilities. However, we had serious difficulty conducting tests on some of the subsystems, as the base ROV experienced difficulties that have not been addressed since previous teams. In the end, given a combination of these unforeseen issues and time constraints, we were only to run a single test of our arm and claw subsystems, only verifying basic movement capabilities in water.

We found many physical constraints in our design throughout our integration stage that led to manufactured parts needing to be fixed or replaced, delaying testing multiple times. For example, when attempting to run a dry bench test of arm movement, the torque applied to the PETG link connectors was enough to warp the parts, rendering them useless. Dry bench testing of the arm and claw subsystems was not conducive to the weight of our parts, requiring the buoyancy force from the attached subsea foam to prevent excessive loading on each part. This presented another major issue: without the possibility of dry bench testing, we would need to ensure the Nautilus would be fully waterproof, something not tested in years, before proceeding with any practical testing of our manipulator.

Unfortunately, ensuring that the Nautilus was waterproof was an extremely difficult task. It was decided, therefore, to test the arm and claw subassemblies separately, without them attached to the Nautilus. We did this by attaching the arm/claw assembly to a 1” square aluminum bar and dunking it below the water of a testing tank, and simply visually testing parameters from above the surface and with a GoPro below the surface. Although this setup allowed us to observe our manipulator’s movement and gripping capabilities underwater, we accepted that it would not be sufficient in demonstrating compatibility with the Nautilus, nor could we test the sample storage subsystem. This testing setup can be seen in Figure 5.2.



Figure 5.1: Celebratory ladder stance after building the testing tank

Although our tests revealed some significant integration and practicality issues, the demonstrated movement capabilities of the arm and claw subsystems were encouraging. As shown in Figure 5.3, the arm was able to maneuver smoothly between folded and fully extended positions without compromising the structural integrity of our parts. This highlights the effectiveness of the subsea foam in reducing the load on components while not providing too excessive of a force that the arm is difficult to control. We are confident that our design can be robust during underwater movement. We also attempted a sample collection by trying to have the claw grasp a small PVC joint at the bottom of the test tank. The claw force from the servo motor was sufficient for grasping the part and briefly lifting it a few inches off of the ground. However, the PVC and the claw parts proved too smooth to keep the part held for longer than a few seconds. We believe that our claw design would have an easier time collecting less smooth rocks and sand, but this could not be tested in our project. Other problems needed to be addressed throughout testing were; cable management, cable connections, and tube sealing. The cables to each servo were easily tangled due to their stiffness during motion. The connectors in the electronics tube were also struggling to stay connected and caused the arm to function uncontrollably and lose connection with the remote control. This was solved for the time being,

but a more effective solution, such as soldering, must be implemented. We also need to replace all O-rings to create more confidence in our seals to test in Tahoe with the entire ROV. Overall, we feel that our test was able to prove the potential of our manipulator concept, but practicality issues will, for now, prevent further implementation of our design. A summary of these testing results can be found in Table 5.1.



Figure 5.2: Testing manipulator in pool



Figure 5.3: Screenshots of below water testing footage

Table 5.1: Testing Status

Results/Comments	Request	Priority
Not tested	Collect multiple samples on one excursion	3
Not tested	Timely (collect multiple samples in the span of one morning)	5
Not tested	Able to collect rocks, mud and silt (various types of sediment)	5
Accomplished: Space available by design, claw able to hold a plastic sample of this size	Samples up to 2x2x2in	2
Not part of design	See the layering in a couple inches of sediment	2
All parts rated for depth, but not tested	Function at a depth of 300ft	2
Not tested	Grip and break off thin rock layers	2
Not tested	Store samples during excursion	5
Not part of design	Accurately identify and record coordinates of where a sample has been taken	4
Accomplished: Claw can be easily removed via single pivot screw	Compatibility with existing tools/ potential for modular claw attachment	3
Not tested	Can move or leave instruments	1
Not tested	Reduced effects on ROV's motion and stability	5

Not tested	Doesn't affect ROV's neutral buoyancy	5
Not within scope	Visual readings of ROV's distance from the ground on descent	3
Not within scope	Ability to identify size and color of things seen in the camera (better imaging)	1
Accomplished: Arm attachment is removable, but cables cannot be removed	Manipulator system is fully removable	5
Accomplished: arm and claw assembly can fit in a 2' x 2' x 2' box	Manipulator system is easy to store and transport	4
Not accomplished	Thorough documented procedures from attaching, using, removing and storing	4
Not tested	Takes less than 3 tries for a trained user to achieve a given task	4
Not tested: Future work/coding improvements required	Anyone can be trained to use it/ not overly complicated to control	3

Section 6: Team and Project Management

It is easy to overlook the importance of the organizational aspects of making an extensive design and technical project come together. While most of this project was calculations, design iterations, manufacturing, and assembling, administration and organization were constant aspects of making sure we met our financial and calendar goals. We used various methods to track our spending and efficiently make progress on the project.

6.1 Supplies Purchasing

6.1.1 Budget

A goal for our sample collection system was to be less expensive than existing similar solutions on the market. However, we also had limitations to our spending based on what we were given from Santa Clara University. The school of undergraduate admissions gave us about \$500 per team member (\$2490), while the Robotics systems lab offered us an additional \$2500 to use.

Below, in Table 6.1, is a simplified and initial version of our budget used to submit our funding request. It anticipated what our costs for this project should roughly be. We made this budget after researching some costs of the materials we would need for our initial design but understanding the details of this budget were bound to change. It over-estimated costs for many categories to consider the unpredictable additional costs that were bound to (and did) happen as we improved upon and iterated our design. For example, we never purchased a crane or device to lower the ROV into the water, nor did we go for the tool sled design iteration requiring an aluminum sheet. We did, however, need to spend more on more servos and stronger servos.

Table 6.1: Preliminary Budget with Funding Type

Item	Estimated Cost	Type of Funding
5000 Aluminum sheet for sled assembly [23]	12ft sections of tubing, (3x2in) x3 = \$1000	RSL

Aluminum to be machined for custom sampling apparatus	\$500 (includes machining at Britelite)	RSL
Waterproof Servo Motors	\$380 x 3 = \$1,140	School of Engineering
Raspberry Pi/ Arduino	\$200	School of Engineering
Crane/Device to lower the ROV into the water	\$500	RSL
Travel Expenses	\$300	School of Engineering
Miscellaneous Hardware	\$200	School of Engineering
Waterproof Housing for additional electronics [24]	\$450	School of Engineering
Miscellaneous Electronics	\$500	RSL
Cabling	\$200	School of Engineering
Total	\$4990	
Total from Undergraduate Programs	\$2490	
Total from RSL	\$2500	

We updated our budget regularly to track these changes and eventually made a sheet on which we marked items as we purchased or made them, organized by subsystem. This full sheet referred to as our Bill of Materials (BOM) and Budget combined, can be found in Appendix E, while Figure 6.1 gives an idea of its layout. Figure 6.2 shows a total that updates as we add new items to ensure we stay within our allocated budget.

Table 6.2: BOM and Budget Tracking Sheet Layout

1	A	B	C	D	E	F	G	H	I
	Assembly	Part	Manufacturing	Description	Cost Per Part (estimates <i>italics</i>)	Quantity	Total Cost	Type of Funding	Status
2	Claw	Waterproof Servo	Bought	Power Unit	\$381.99	1	\$381.99	School of Engineering	Requested in Quartzly 1/21, Ordered 1/25, Recieved 2/3
3		Frame	PLA 3D	Connector for all parts	\$0.00	1	\$0.00	Maker Lab	Design in Progress - to be prototyped by 2/28
4		Piston	PLA 3D	Linear Power	\$0.00	1	\$0.00	Maker Lab	Design in Progress - to be prototyped by 2/28
5		Horn	Aluminum Machined	Rotating Arm	\$0.00	1	\$0.00	Machine Shop Scrap	Design in Progress - to be prototyped by 2/28
6		Connector	Aluminum Machined	Transfers Motion to Claw	\$0.00	4	\$0.00	Machine Shop Scrap	Design in Progress - to be prototyped by 2/28
7		Claw	PLA 3D	Scoops material	\$0.00	2	\$0.00	Maker Lab	Design in Progress - to be prototyped by 2/28
8		Claw Servo Mount	3-D Print	Holds Servo to frame and claw	\$0.00	1	\$0.00	Maker Lab	Being 3-D printed
10		M4x15mm hardware	Bought	Servo to Horn	\$10.00	1	\$10.00	School of Engineering	Home Depot
11		.25" Roll pins	Bought	Claw arm, horn connections	\$10.00	1	\$10.00	School of Engineering	Home Depot
14	Sample Storage	Waterproof Servo	Bought	Power Unit	\$381.99	1	\$381.99	School of Engineering	Requested in Quartzly 1/21, Ordered 1/25, Recieved 2/3

***Note: Many parts have zero cost because they were made using scrap parts (ie. Delrin and acrylic as well as some aluminum tubing) or made using 3-D printing which we have unlimited free access to on campus for class related work.

Table 6.3: Cost Summary for BOM and Budget

Cost Summary	
Total Budget	\$4,990.00
Total Spending	\$4,457.68
Total Spending (RSL)	\$2,120.15
Total Spending (School of Engineering)	\$2,337.53
Total Budget Left	\$532.32

6.1.2 Purchasing

When it came to the actual act of material purchasing, we had one designated person conduct all of it through Quartzly or by emailing Dr. Kitts from the RSL. This year, Quartzly was used by all the Senior Design teams and streamlined all purchasing using the School of Engineering’s funding. Having one designated purchasing person prevented accidentally ordering things twice and kept our running total more accurate. It was most efficient for one of us to complete the training and manage the funds.

6.2 Timeline

To make sure that we met important deadlines, team management was vital. The same person who managed to purchase was delegated as our “team manager” took care of organizing meetings with stakeholders and was the main point of contact for our team. This person also took care of sending out meeting summaries and calendar invites for meetings.

6.2.1 Timeline

To keep track of our project’s pace, we created a timeline of key milestones and deadlines to meet (Table 6.2).

Table 6.4: Key Project Milestones and Deadlines.

Date	Event Description
Oct 2, 2021	Project Proposal
Oct 31st, 2021	Project Funding Request
Nov 6, 2021	Safety Proposal
Dec 8, 2021	CDR Report and Presentation
Jan 22, 2022	Budget Update due
Feb 2, 2022	Finalize CAD Assembly
Feb 12, 2022	Ethics Analysis due
Mar 25, 2022	Manufacture Subsystems
May 12, 2022	Senior Design Conference
May 26, 2022	Draft of Thesis due
June 9, 2022	Thesis Library Submission Deadline

6.2.2 Timeline Management

With five team members and broad project scope, to keep track of goals and keep each other accountable, we used Weekly Activity Reports (WARs) and Smartsheets consistently during our first quarter. Then, after developing good habits and seeing what worked best for our group, we used only Google calendar and a group text chain to manage ourselves.

WARs helped us organize our more short-term goals, going through the tasks just for the previous week and the following week and who is responsible for them. We could review how much we were able to complete the task, try to assign similar amounts of work to each other based on hours, and review each other's progress and plans. However, past the planning stage in the Fall quarter, we had delegated long-term tasks to one another, and WARs were no longer worth their time.

Week: 9

WEEKLY ACTIVITY REPORT (WAR)
ME 194 - ADVANCED DESIGN II - Fall 2021

TEAM: Marine Robotics

Members
Noah Villar- NV, Valeriya Chulyukina- VC, Kekoa Blair- KB, Nathan Burke- NB, Mandeeep Singh- MS

Topic	Team Members (Initials)	Hours	Total-hours	% Completed	Progress / Accomplishments	Future Plans	Problems / Questions
Weekly meeting with Dr. Kitts	KB, NV, NB, VC, MS	1	5	100	Discussed potential changes, and what to try out on the electrical side of things	Play with tinkercad and other mockups of ideas discussed over break	
Update software and electrical diagram to be compatible	NV, NB, MS	1	3	100	Looked into connection between ROV and appendage arduino(compared options)	Need to take out electronics tube, try out a couple options	
2nd Round of Prototyping	KB, NV, NB, VC, MS	2	10	25	Asked about servos and existing equipment in lab	Will work on over break- try out with servos after break	
Correct and resubmit hazard form	KB, NV, VC	1	3	100	Got Kitts signature, submitted		
Started writing up final CDR report	KB, NV, NB, VC, MS	1	5	50	Have a rough draft		
Update Smartsheets timeline	VC	2	2	75	updated	keep updated as we go, update next quarters/ add detail	
General Team Meetings	KB, NV, NB, VC, MS	1	5	100	Tried to take electronics tube apart, got more guidance from last years team	get arduinos to talk to each other and connect with servos	
Write up Goal #3 Proposal and Pres	KB, NV, VC	3	9	100			
Total Man-Hours			42				

Figure 6.1: Screenshot of Weekly Activity Report (WAR) from Week 9 as an example of how we set goals for the week.

Smartsheets are a tool that is commonly used in industry, and students can get a free license. It has many capabilities, but at the most superficial level, it allows you to organize tasks

with subcategories, assign them to team members, set start and end dates, and mark them as complete. In addition, one can generate Gantt charts and flag tasks as their deadline approaches. It also has options for automation that we did not utilize this year but has much potential for similar projects. These options include sending emails, reminders, or request updates based on triggers such as imputed dates or completion of tasks. Figure 15 shows how we utilized Smartsheets in the fall quarter, and Figure 16 shows an overview of some of the more considerable deadlines over the rest of the school year.

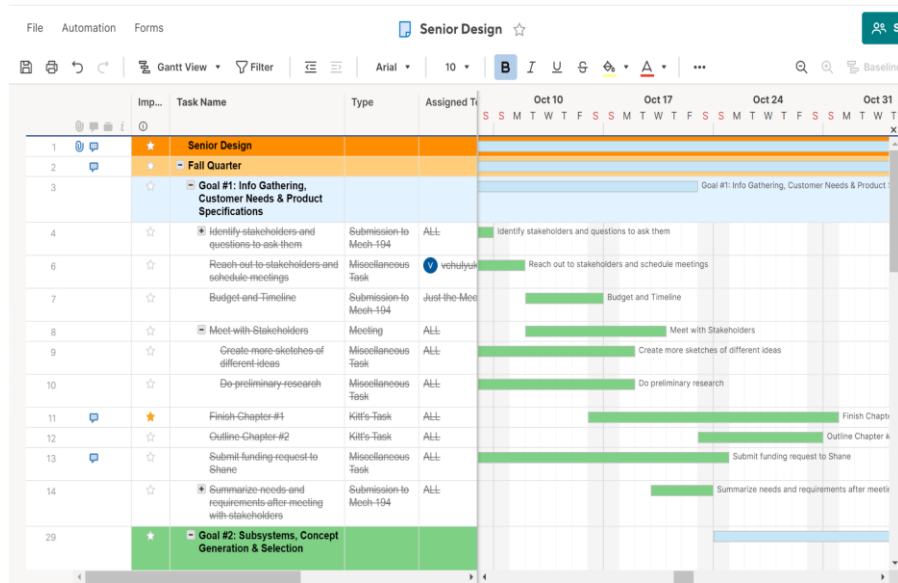


Figure 6.2: Screenshot of Smartsheets (first part of fall quarter)

Imp...	Task Name	Type	Assigned To...	Estimated Time of Task (total)	Start	Finish	Status
	(share prototype)						
☆	Prototype Round #3	Submission to Mech 194	ALL	10 hours	11/29/21	12/03/21	In Progress
☆	Goal #3-Report	Submission to Mech-194	ALL	6-hours	11/20/21	12/04/21	Complete
☆	CDR Report and Presentation	Miscellaneous Task	ALL	10 hours	11/22/21	12/08/21	On Track
☆	Conceptual Design Review	Presentation	ALL	1 hour	12/08/21	12/08/21	Not Started
★	Winter Quarter				01/03/22	03/11/22	
☆	Goal #1: Do Preliminary Calculations				01/03/22	02/01/22	
★	Goal #2: Create CAD Model				02/01/22	02/14/21	
☆	Register for Conference	Miscellaneous Task	ALL		02/06/22	02/06/22	Not Started
★	Goal #3: Build Formal Prototypes				02/14/22	03/11/22	
★	Spring Quarter				03/28/22	06/03/22	
☆	Goal #1: Test Prototypes				03/28/22	04/30/22	
★	Goal #2: Adjust and Retest Prototype chosen				04/30/22	10/05/21	
★	Senior Design Conference	Presentation	ALL		05/12/22	05/12/22	Not Started
★	Goal #3: Finish Paper, charts and Presentations						
☆	Senior Design Thesis Library Submission Deadline	Miscellaneous Task	ALL		06/09/22	06/09/22	Not Started

Figure 6.3: Screenshot of Smartsheets showing some of the main milestones.

Google calendar and text proved to be the most maintainable for our group’s dynamic. Once we got into the rhythm of things, we were able to send summaries of meetings and have a shared Senior Design Google Calendar where we could schedule meetings with locations or Zoom links. This was also convenient as we stored all our shared documents within the Google Suite as well.

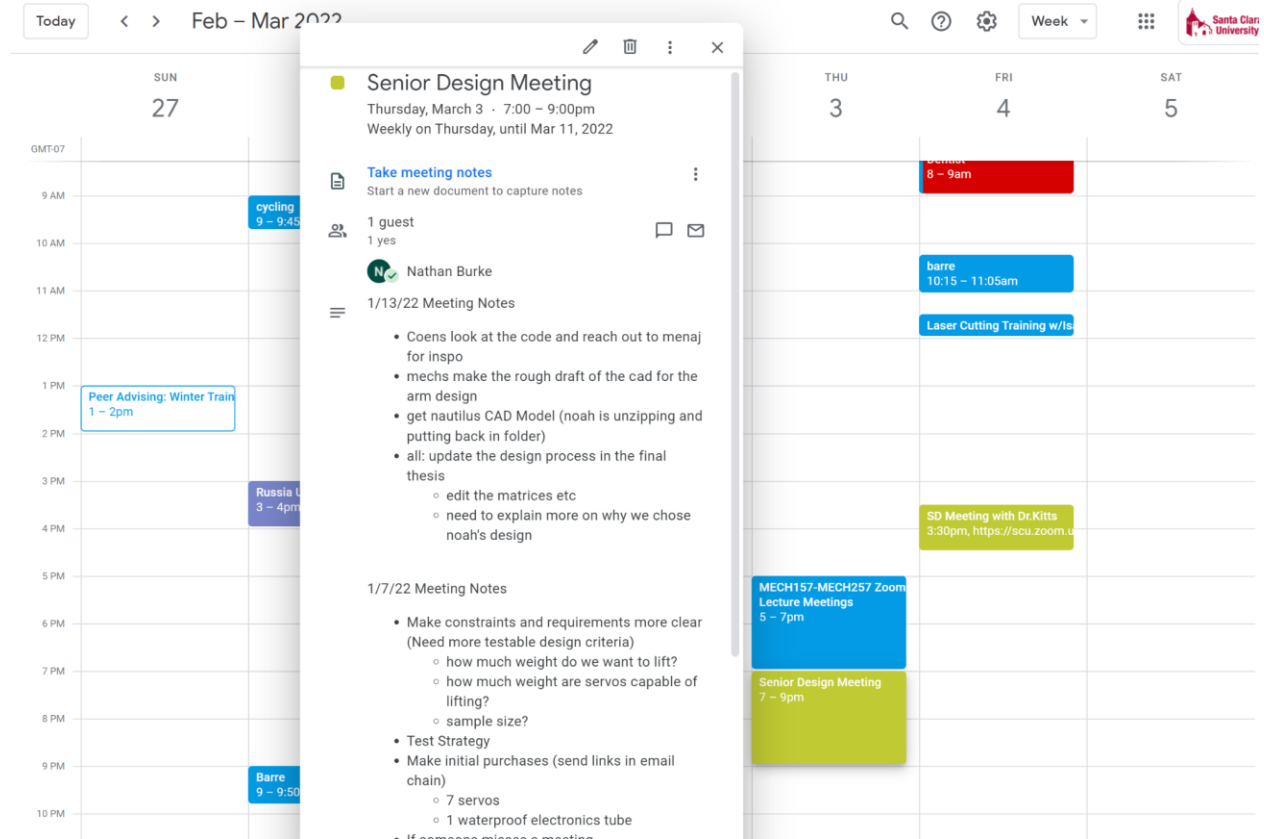


Figure 6.4: Screenshot of Google Calendar.

Section 7: Professional Issues

7.1 Usability

Initially, the operators used a single Xbox-style controller to maneuver the Nautilus ROV. However, when we first tested the Nautilus' capabilities, we found it quite taxing and focus intensive to keep the ROV in a semi-stable position to view objects. It would be tough for a single operator to also manipulate an arm alongside this. The complexity of the arm would be limited since there were not many free buttons available on the controller. We wanted to separate control for the robot and the arm, so we added a second controller.



Figure 7.1: Dual Controller Setup.

This allows the ROV pilot to only focus on movement; they do not have to multitask moving the arm and keeping the robot still due to water currents. Since the original system was not designed to use multiple controllers, we had to modify the code. Nevertheless, having a dedicated controller gives us the freedom to design the controls however we want and make it easy for the second operator to manipulate. We do all the controller mapping calculations on the topside computer to send the servo values directly to the servo controller. This reduces delay as the Arduino does not have to process the packet, complete the calculations, and forward the updated packet to the servo.

7.2 Ethics

The ethical implications of underwater research are complicated, as many things are once you dive below their surface. Due to its clear contrast to our daily life, underwater research requires unique systems to give access to environments rarely viewed by humans. A lot of the underwater research done today is with inaccessible, expensive, heavy, gas-guzzling machinery. Considering all this, our goal is to give the maximum capability to researchers with minimal investment and environmental impact. Our project has set out to create a mechatronics arm for one of Santa Clara University's University (SCU), Robotics System Labs (RSL), and Remotely Operated Vehicles (ROV). This ROV is orders of magnitude cheaper and easier to deploy. It would open doors for the Robotic Systems Lab's research partners in Monterey and Tahoe to partake in small, cost-effective sample retrieval that is not viable or significantly more difficult with larger ROVs equipped with sample-taking devices.

Many nearshore ecosystems are disproportionately not researched below the surface because of the type and size of standard samples taking ROVs today. Increasing our ability to research these nearshore ecosystems efficiently will increase researchers' ability to grasp a whole picture of the ocean's ecosystems and geology and lakes, and other more shallow, calm water bodies. Better understanding our environment will allow us to take preventive measures and protect future generations. In ethics, deontological utilitarianism would refer to this as preserving their negative rights. We have a duty not to disturb the well-being that others are born with. Geologists could use our tool to understand our impact on the environment and historical patterns. This information can be used to find natural resources or prevent natural disasters (and

even study the effects of global warming!). This can save the lives of animals and people. Our targeted effect is very high level and will not directly affect anyone, but an increased understanding of underwater ecosystems can make a compounded difference in the future.

When engineering, it is essential to understand all the effects of what you are doing and not just get lost in the overarching goal and explicit rules and requirements from authority figures. Deontology refers to ethics based on rules, laws, and respecting rights. This is usually covered in engineering societies' codes of ethics and workplace guidelines. However, other forms of ethics should also be considered. Virtue ethics and utilitarianism (teleology) are other lenses used to look at ethics that can help to avoid missing other essential aspects of being an ethical engineer. Projects should have subgoals, and engineers should have traits that help them meet them. For instance, when trying to create a faster car, safety and environmental impact and other goals should be tied in. In our case, some ethical "subgoals" for us to consider are minimizing harm and disturbance to the ocean floor or lakebed, reducing power use, and using recycled or scrap materials where possible. Based on many observations, we have done our best to create a system that will leave no trail, constructing it with corrosion-resistant materials that will not leave chemical residue under the oceans and increased visibility and controls to avoid colliding with wildlife. Our project embraces the first fundamental principle of the ASME Code of Ethics: "using their knowledge and skill to enhance human welfare" and our environment's welfare (highlighted in the Canons). Our project is us practicing using what we are learning to better improve the lives of ourselves and others in the long run. We will practice care for others and the environment, patience, and commitment to the public good. The broad scope of our project will require courage and teamwork too.

As with any robotics project, especially meant for underwater use, there are many safety risks to address. We take this into account on every mission, checking the weather and wave conditions to ensure we are safe. We also are vulnerable to risks associated with our equipment (more specifically, electronics and batteries), and water does not mix safely. Unfortunately, we cannot eliminate many of these hazards, but we can reduce their risk with proper training and procedures. In addition to ethical risks to ourselves and the people around us, we have to make sure we are careful to reduce adverse effects on plant and animal life, as mentioned before, both in our project design and manufacturing and while it is in use.

7.3 RSL Lipo Safety and SCU Marine Operation Safety Guidelines

The RSL and SCU have safety guidelines. We had to operate within and use our safety judgment beyond these guidelines. The RSL requires Lipo Safety training for any individuals using lipo batteries. SCU also has stringent guidelines for marine operations due to the inherent danger of the ocean and lakes. Beyond these guidelines for our safety, we followed ROV deployment procedures to protect equipment and boats.

Lipo safety is severe, and mishandling of a lipo battery can result in fire, explosions, or permanent damage to the battery. Lipos or Lithium Polymer Batteries are used in many hobbies and professional applications due to their constant discharge and low degradation over time. However, they come with many caveats; the charging process is complicated and requires an understanding of common battery labelings to be done correctly. It also requires constant monitoring of voltages during use to keep them in good health. To mitigate their dangers and maximize their effectiveness, the RSL requires them to be checked, charged, and stored in specific ways. In addition, every lipo must be charged under the supervision and be stored and transported in a fire-safe container. By following the procedures set forth, we can ensure our safety and the longevity of the RSL's resources.

SCU marine operations safety guidelines are set out to help us ensure safety throughout deployments to Tahoe and Monterey Bay. Many of these guidelines we learned in Engr 180, marine operations class. This class goes through the critical steps for deployment, such as pre-deployment testing, safety officers, and docking procedures. This system gives each person specific jobs and roles to ensure everyone is productive and safe. Often these procedures are different per robot and ship but are recorded and accessible from the RSL.

Section 8: Summary and Conclusions

8.1 Project End State & Outcomes

Of our six main requirements, we found varying success completing and proving them. Four of the seven requirements were feasible and the other three remained untested but were theoretically verified through mathematical calculations and have the potential to be tested by a future team. We have yet to prove the requirements and our robot's competence in the environment, a deployment to Lake Tahoe, where Nautilus is intended to be used.

Our first parameter was to collect three sediment samples in 45 minutes, this requirement should be feasible with further integration of the arm and updates to the storage system during a future rendition of this project. Currently, the storage system is not capable of rotation to collect and index multiple samples. We found that the gear train selected is too small resulting in planar instead of rotational force on the sample pan, and that friction is not as negligible as much as we would like it to be. To confront these issues, we've ordered larger gears and a thrust bearing to replace the Delrin fixture holding the pan to the frame. In addition, the arm can move under control of the pilot with significant speed but lacks precision due to lack of end effector control and bugs in the controller making its connection spotty at times. However, the manipulator end effector could reach intended workspace as shown by our kinematic analysis and somewhat from our testing in the test tank.

Our second requirement was to collect samples of two cubic inches or greater. This requirement was designed for using a volume calculation of the claw and storage but has yet to be tested picking up rocks or sediment. In our evaluation, there was only one test where the arm was fixed onto the ROV as it would be on a deployment. We attempted to pick up a PVC fitting, which pushed the size limitations of the claw and was significantly smoother than real life samples making it impossible to pick up. In addition to this, we adjusted the angle of the claw with respect to the arm mid-testing and broke the joint by overtightening it. This happened just days before the conference which limited our ability for testing with other mediums. We performed other tests with the arm not on the ROV and somebody holding the frame attachment. In this test, we were able to move the arm down, orient the claw, and pick up a small rock. However, this does not simulate a real deployment or scenario whatsoever and was more done to

test ranges of motion and proper functionality of the arm and claw. With this in mind, the end effector was designed with the intention to be easily swapped out, so with more time, a new scoop could be 3-D printed and even adjusted to be able to pick up smoother items.

Our third requirement of lifting a sample of 1.6 pounds or greater was verified through calculations, but has yet to be proven through underwater testing. It cannot be tested out of the water due to a reliance on buoyancy underwater. During our underwater testing we had to dismount the arm from the ROV to safeguard against water leaking into the electronics tube with old O-rings, this took away most of our vertical workspace in the testing pool to attempt to find the max lifting force. With new waterproofing gear, the ROV could be set down in the testing tank and one could more easily test the manipulator's maximum ability to lift heavy samples.

Our fourth requirement, a 300-foot depth capacity for the whole ROV and arm system - will most likely never be tested due to the locations we deploy not being deep enough and failure of this test would be expensive and hard to recover from. However, all the machinery we bought are rated from the manufacturer to 300 feet depth and the pressure tests have been conducted that corroborate this with new O-rings.

The fifth requirement was that the manipulator system be a modular part that can be easily removed from the ROV. Our design requires bolted holes in the frame and one wire connected to the main tube, allowing the entire sample retrieving system to be removed within an hour with screwdrivers, or even faster with a hand drill.

The last requirement was our manipulator be neutrally buoyant. Our foam additions have created a neutral buoyancy manipulator in an underwater environment shown by our buoyancy calculations, as well as testing where the servos are minimally strained while holding the arm stationary under water. One could see the strain and bending of the arm above water, and see it straighten out as we lowered it below. This buoyancy is only maintained neutral at the tip as it was designed to and does not influence the balance of the rest of the ROV. Any disbalance of the ROV is contributed to by our electronics tube, but all of this is solvable on deployment with the adjustable dive weight system designed and implemented on the ROV already.

8.2 Going Forward & Future Impact

Our project has been an insightful learning experience and proof of concept that a serial chain manipulator can function at this size and budget. As with any long project, time management and setting realistic goals was a challenge, and many parts of the design that could have been tested or fixed on campus remained unfinished. There is plenty of room for more improvements and iterations in addition to those suggested in Section 8.2.

The control software is fundamental and needs to be improved since we only had limited time to test and calibrate the controls, they are not reliable, and bugs remain in the control loops that leave the arm controlling itself sometimes. Improvements could be made to make the servos move more smoothly and accurately with the current control scheme. Furthermore, many unused buttons on the second controller could be mapped to various functions, such as automated sample storage. A more complex system such as endpoint servo control, as seen in section 3.3.4, could be implemented by a future team. This alone would significantly improve user control and make it much easier to collect samples. Another additional item that should be added is a battery holder for the electronics tube. This will keep the battery and electronics from shifting around during deployment. Wiring within the tube is still mainly connected with breadboard jumper cables that are not soldered in place, allowing them to come unplugged under gosing conditions, solvable by the battery holder. Finally, a user manual needs to be created. This would help future teams understand how to operate the arm, remove it from the robot, and understand how it works so they can improve upon our design.

For future teams, several items could be considered as topics of interest. One might be a custom storage/transportation box. This would keep the arm safe and all the components together during transport as it currently does not have a dedicated storage container. On the software side, variable servo speed control could be implemented along with endpoint control to elevate the control system. The arm has a very rudimentary form of variable speed control based on the position of the control stick. However, easing, which uses quadratic functions to make servos ramp-up speed very smooth, would streamline sample collection. Therefore, variable speed control combined with endpoint control would be ideal. For the claw, future teams could create their designs for specific uses, expanding the arm's functionality by simply changing the end effector. For example, if the claw is made larger to collect larger samples, the servos could be

replaced or customized to put more force to accommodate the extra weight.

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Appendix

Appendix A: Stakeholder Meetings Transcripts

Dr. Rich Schweickert: Dr. Kitt's partner for about 20 years in terms of their annual work in Lake Tahoe. For the Nautilus team, he is one of the main scientists for whom the RSL provides services. Most of these in the past have been imaging missions, to collect video of "targets" on the lake bottom, but are now starting to think about enhancing that capability and adding some possible physical intervention/collection.

Dr. Schweickert's studies would try to sample sedimentary material, such as rock, mud and silt, up to several inches. He noted that soft silt could even be gone after with a simple scoop. In addition to the sedimentary material, he also expressed interest in gripping and breaking odd thin layers of rock using the manipulator. When asked what traits he would like us to prioritize, he noted a sample rack capable of documenting samples and logging their location on the bottom of the lake. During our discussion, we also concluded that 45 minutes is a reasonable amount of time for the ROV to be on a given mission, and any number of samples that can be retrieved in this time frame would be helpful. He also hoped that the ROV would continue to be operable at 300ft below the surface.

More out of our project scope, but important for future additions to the ROV, Dr. Schweickert suggested a portable label printer to mark samples, a way to scale objects seen by the camera and more detailed images.

Dr. Geoff Wheat: From UA Fairbanks (but located mainly in Moss Landing, and an adjunct researcher at MBARI), Dr. Wheat is a geoscientist Dr. Kitt has been working with for about 20 years. He specializes in how water flows and moves chemical deposits around in Monterey Bay. He's been a sponsor of some of the RSL's work, a collaborator on several R&D efforts (like the current NSF borehole sampler), and a scientist for whom the RSL has developed capabilities. His interests lie in collecting rock samples up to the size of a hand, as well as moving and leaving instruments, such as temperature probes, up to 12"x 20" in size, as well as some sediment sample gathering. He thought that our preliminary goal to collect three to four samples was realistic. He

also suggested a three-tong arm with a $\frac{3}{8}$ " divet customized to hold specific tool types, but we did not go with this design after more consideration because it was not very versatile.

Dr. Wheat also emphasized the importance of consciously choosing our degrees of freedom suggesting we use a hand movement, a telescoping in and out and a wrist turning movement, as well as making sure we acknowledge the center of mass. For instance, where do we store the sample? Where is the camera relative to the manipulator? The lights? How does added weight and buoyancy affect the movement of the robot? Movement for underwater robots with a tether can be a huge limitation as is.

Mr. Bill Kirkwood: Eminent engineer at MBARI and another collaborator of the lab's for ~20 years. Bill has done some adjunct teaching for Santa Clara University and is working on the HURACAN AUV project in the RSL. He has an extensive background in AUVs. He said it is most important to rank things and have reasoning during the execution as well as document the engineering process as we go. From his experience and for his interests, he said seeing layers in sediment is not as important, but in general, a push core would be standard for this type of sampling, but most people in our capstone audience won't know that, but it might be good to acknowledge that we know what a push core is and why we are choosing not to use one. Existing push core and other instruments have either a baseball or T hold to consider if we had wanted our design compatible with existing instruments in the field.

Additional points that Dr. Kirkwood made included to be careful with 3-D printed parts. They can take on water if they are porous. This is why we chose 100% infill for our parts, and still acknowledge there is some risk of air bubbles in the parts anyways. He also suggested bushings for anything that rotates and also suggested a test plan: test in bucket different sediment mixtures (there are standards on army corps engineers) and see how much pressure it takes to take the sample out (can set boundaries for sample types).

- Recommended book: Society of naval architects and engineers

Dr. Kirkwood's recommended order to focus on tasks:

- Make sure we understand the requirements we have to meet, and then rank specifications we want to build (what HAS to work vs what can be dropped in a time crunch)
- How is it going to work (procedure) test plan?

- Preliminary concept designs (maybe 3)
 - What do they need? What are their limitations?
 - Down select to final design (by January?)
 - Test it! Set boundaries, pounds force, types of materials
 - Maybe make up our own instrumentation (ie test thrust with calibrated rubber bands)
 - Identify and arrange where we will do in water test
 -

Mr. Thomas Adamek: A prior RSL grad student and staff member, and when he was a staff member he was one of the leads on the marine program, developing/maintaining/operating systems, etc. He's got a lot of field experience and wisdom in marine systems and beyond. He's currently part of the RSL alum cohort working at OnePointOne. The research he facilitated was for the SWATH mapping system - looking at rocks and mapping Tahoe for interest areas. He noted that for projects such as ours, we should focus on what's going to work and what's not-having reality checks and breaking down our goal into steps as well as having good communication between major groups. He encouraged us to “get our motor spinning quickly” and think iteratively.

Recommended source:

<https://www.nauticexpo.com/boat-manufacturer/rov-manipulator-arm-26019.html>

Jeff Ota: Jeff Ota helped start RSL more than 20 years ago and knows our marine robotics program well. He gave us a lot of good advice on working on a senior design project in general, such as how decisions we make now dictate Spring and Winter Quarter results, so keep the design simple and achievable, get in the machine shop early, iterate quickly and multiply the time we think a given task will take by five. On the same topic, he suggested getting the requirements down and clear from our stakeholders and keeping them updated, articulating back to them what we are understanding, and showing them prototypes to make sure we are interpreting them correctly.

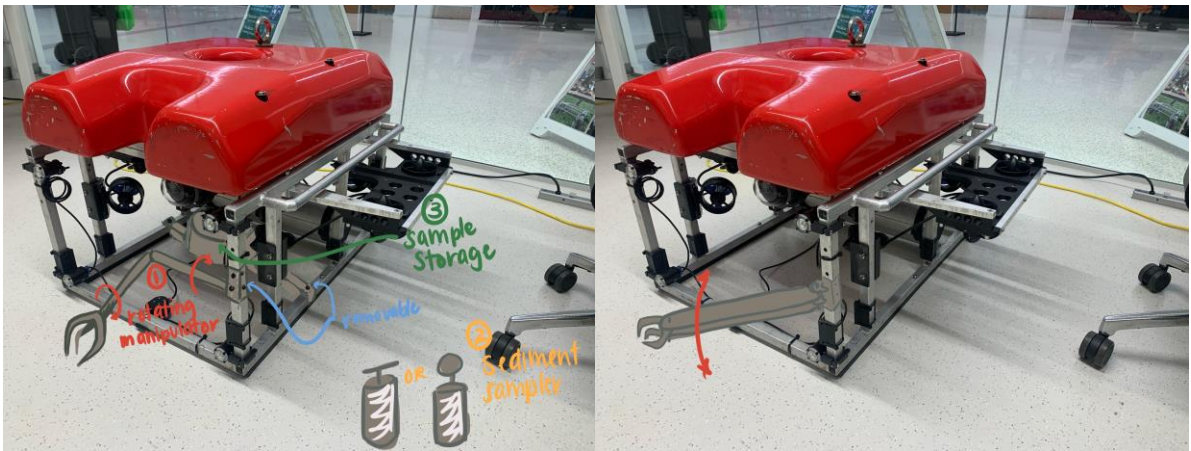
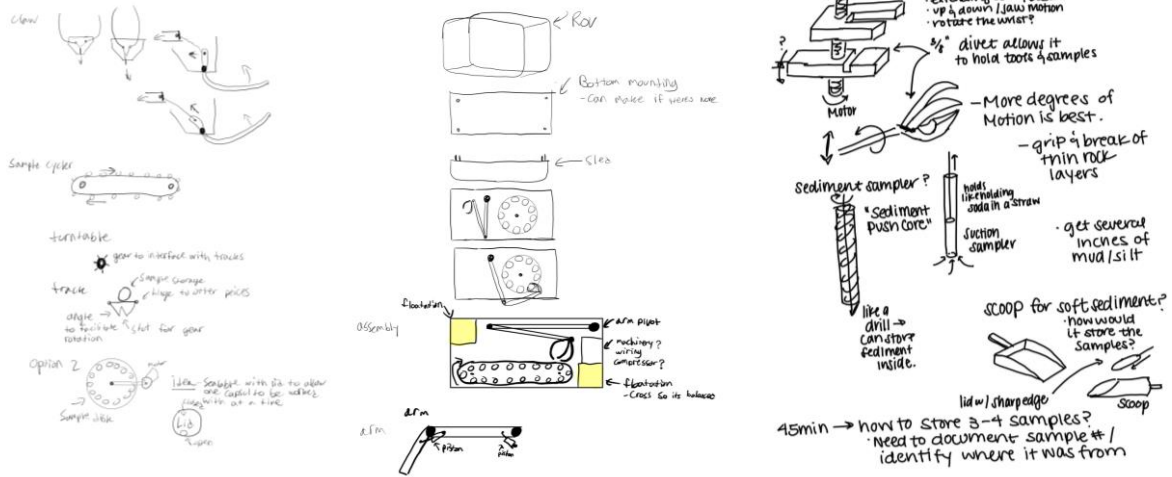
Jeff Ota also suggested we look more at previous designs, for instance the early reports from 1999 to 2005 include a lot of mechanical designs. There was another gripper, referred to as

the “Tako”, that the RSL did with a Japanese university. Also, another ROV, the “Manterris”, had a sled that could be dropped and stays on the bottom which the ROV would slam onto to secure it.

We also learned that hydrodynamics is something we need to investigate - if our ROV dove forward with the arm, ROV would dip (take into account COM and how it is a wing that can cause it to dive).

Appendix B: Concept Generation

Initial Sketches and Inspiration

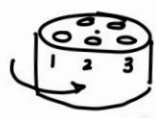


Common for larger ROV to store samples in bucket...



shallow bucket for samples? (simple)

rotating sample holder?



Allows samples to be indexed (identify where they were grabbed)

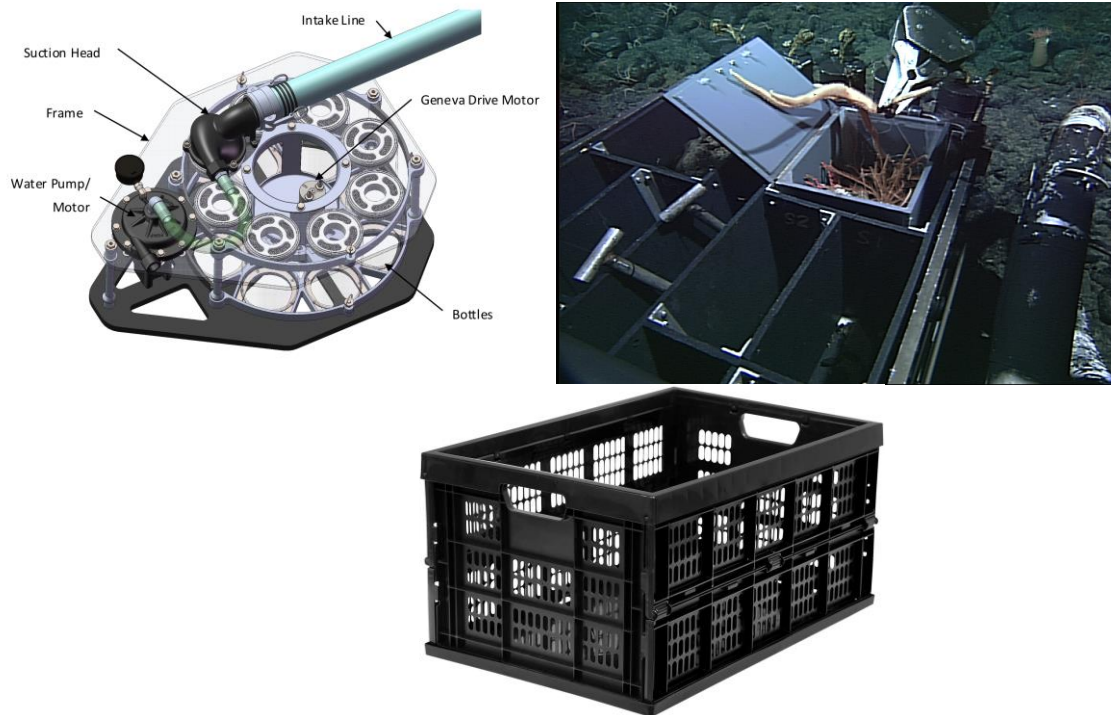


Figure B.1. Initial Sketches and Brainstorming

Other Matrices

Table B.1: Customer Needs Summary Matrix with Quantifiable Units

Requirement	Importance	Quantifiable Units
Retrieve Sediment Samples	1	Visual Layering
Access and retrieve rocks	5	Claw force (Lbf)
Gain Multiple Samples	4	Number of Samples
Reach non-divable depths	3	Feet (ft)
Retain ROV mobility	2	Speed (fts ⁻¹)

Table B.2: Requirement Metrics with Current and Goal Capabilities

Stakeholder Requirements and Metrics	Units	Current Nautilus Capability	Goal

Sediment Samples	Visual	NA	6" layer
Claw force	Lbf	NA	50 Lbf
Claw Size	in	N/A	4"
Multiple Samples	count	NA	4
Depth	ft	300ft	300ft
Mobility	fts ⁻¹	5fts ⁻¹	3 fts ⁻¹

Early Mockups and Prototypes

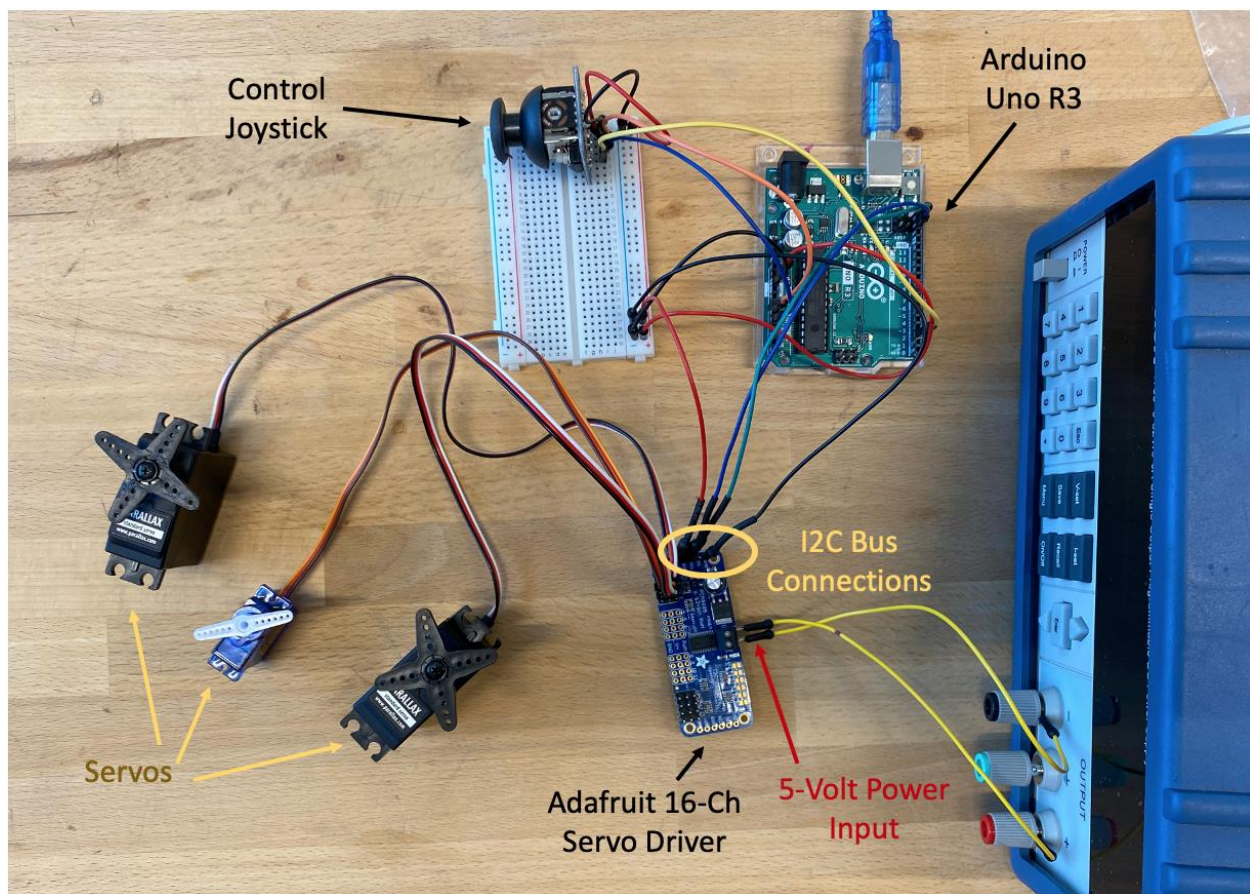


Figure B.2: Electrical setup for last round of mockups

Figure 13 shows the set-up for the electrical mockup that was presented in our Fall Quarter CDR presentation. It was intended to be a proof-of-concept for the I²C Bus protocol, as

our servos, representing the degrees of freedom, were controlled through the protocol by the joystick attached to the Arduino Uno R3, representing the existing Nautilus control module.

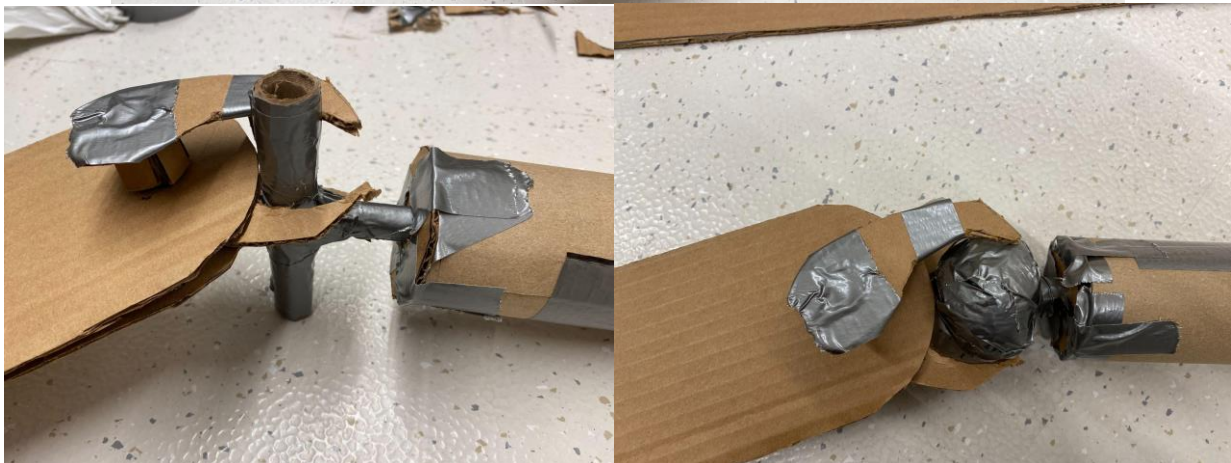
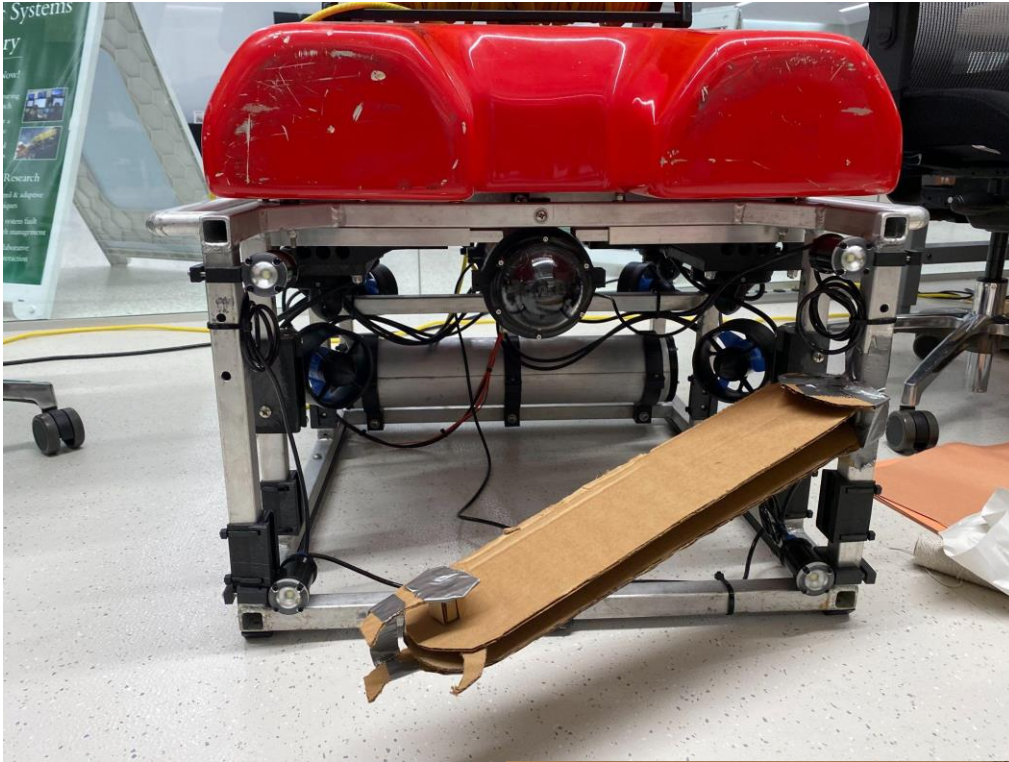


Figure B.3: Initial round of mockups

During our initial round of mockups, we found that this design was too flimsy, and would be complicated to engineer the diagonal portion at the base of the arm, by where it attaches to the

frame. We also noticed that this design would limit our workspace. We redesigned with our second-best rated designs. The setup for this is seen in Figure 13.

Appendix C: Hazard Assessment Form

This form is to be used for student projects where the primary hazards are associated with engineering work (physical, mechanical, electrical, etc.). Chemical and biological-focused projects require a separate form.

Complete this form and obtain all the required approvals (Faculty Advisor, Department Chair, Laboratory Manager, EH&S, etc.) before proceeding with the project. Please refer to the hazard assessment guide for assistance in filling this form.

Project Title: Nautilus ROV Manipulator Team			
Project Team Members: Kekoa Blair, Valeriya Chulyukina, Noah Villar, Nathan Burke, Mandeep Singh			
Project Advisor			
Name: Chris Kitts	Department: Mechanical and Computer	Phone: Ext - 4382	Email: CKitts@scu.edu
Proposed Project Location(s) (Department, building, room#):			
SCDI 1205 (RSL)			
SCDI 1111 (Fabrication)			
Anticipated Dates of Project Duration:			
Sept 2021 - May 2022			
Summary of Project Objectives:			

Design, build and test an opposable manipulator for the RSL's existing ROV, "Nautilus". If time allows, we also anticipate building an indexing sample storage system and a tool to be used with the manipulator for the purpose of sediment sampling.

Hazard Checklist (check all that apply)

Identify all the tasks that must be completed for your project. Carefully evaluate each task to determine if there are any associated hazards. After identifying the hazards of your project, you will be asked to assess the risk connected to each hazard and to identify control measures that will either eliminate the hazard or reduce the risk to an acceptable level. Safe work procedures for each step involving a known hazard will need to be developed.

HAZARDOUS CONDITIONS/PROCESSES/ACTIVITIES		
Electrical Hazards	Mechanical Hazards	Physical Hazards
<input type="checkbox"/> Electrical parts and assemblies > 50V or high current <input checked="" type="checkbox"/> Batteries <input type="checkbox"/> Control Panels	<input checked="" type="checkbox"/> Power tools and equipment <input checked="" type="checkbox"/> Machine guarding/power transmission – gears, rotors, wheels, shafts, belt/chain drives, rotating parts, pinch points <input checked="" type="checkbox"/> Robotics <input checked="" type="checkbox"/> Sharp Objects <input type="checkbox"/> Stored Energy (springs, gravity, pneumatic, hydraulic, pressure)	<input checked="" type="checkbox"/> Extreme temps (high temp fluids: water > 160 °F, steam, hot surfaces > 140 °F, cryogenic fluids) <input checked="" type="checkbox"/> Material handling of heavy objects <input type="checkbox"/> Elevated heights (scaffolding, ladders, roofs, lifts, etc.) <input type="checkbox"/> Overhead falling objects (cranes, hoists, drones, projectiles, etc.) <input type="checkbox"/> Confined Spaces <input type="checkbox"/> Airborne Dusts <input type="checkbox"/> Bonding / Grounding <input type="checkbox"/> Electrostatic Discharge

Reaction Hazards	Hazardous Processes	Other Hazards
<input checked="" type="checkbox"/> Explosive <input checked="" type="checkbox"/> Exothermic, with potential for fire, excessive heat, or runaway reaction <input type="checkbox"/> Endothermic, with potential for freezing solvents decreased solubility or heterogeneous mixtures <input type="checkbox"/> Gases Produced <input type="checkbox"/> Hazardous reaction intermediates/products <input type="checkbox"/> Hazardous side reactions	<input type="checkbox"/> Generation of air contaminants (gases, aerosols, or particulates) <input type="checkbox"/> Heating Chemicals <input type="checkbox"/> Large mass or volume <input type="checkbox"/> Pressure > Atmospheric <input type="checkbox"/> Pressure < Atmospheric <input type="checkbox"/> Scale-up of Reaction <input checked="" type="checkbox"/> Metal Fabrication (welding, cutting, drilling, etc.), Soldering, <input checked="" type="checkbox"/> Construction/Assembly	<input type="checkbox"/> Noise > 80 dBA <input type="checkbox"/> Vehicle traffic <input type="checkbox"/> Hazardous waste generation <input type="checkbox"/> Other (list):

Hazard Checklist (continued)

HAZARDOUS AGENTS			
Physical Hazards Of Chemicals	Health Hazards of Chemicals	Non-Ionizing Radiation	Biohazards
<input type="checkbox"/> Compressed Gases <input type="checkbox"/> Cryogenics <input checked="" type="checkbox"/> Explosives <input checked="" type="checkbox"/> Flammables <input type="checkbox"/> Oxidizers <input type="checkbox"/> Peroxides or Peroxides Formers <input type="checkbox"/> Pyrophorics <input type="checkbox"/> Water Reactives	<input type="checkbox"/> Acute Toxicity <input type="checkbox"/> Carcinogens <input type="checkbox"/> Nanomaterials <input type="checkbox"/> Reproductive Toxins <input type="checkbox"/> Respiratory or Skin Sensitization <input type="checkbox"/> Simple Asphyxiant <input type="checkbox"/> Skin Corrosion/Irritation <input type="checkbox"/> Hazards Not Otherwise Classified	<input type="checkbox"/> Lasers <input type="checkbox"/> Magnetic Fields (e.g. NMR) <input type="checkbox"/> RF/Microwaves <input type="checkbox"/> UV Lamps	<input type="checkbox"/> Bsl-2 Biological Agents <input type="checkbox"/> rDNA <input type="checkbox"/> Human Cells, Blood, BBP <input type="checkbox"/> Animal Work <input type="checkbox"/> Other (List):

Description of Potential Hazards

Provide a summary of the procedure and describe the risks associated with each hazard that you have identified above or on the previous page. Use one box below per hazard. You may add supplemental pages if needed. Define the hazard control measures that will be employed to minimize the risks based on the hierarchy of controls (elimination, substitution, engineering controls, administrative controls, PPE), and then describe specific control measures you will use (e.g. Work on system de-energized, receive hazard-specific training, shield hot surfaces, guard pinch points, relieve stored energy, wear protective equipment, use less hazardous chemical, etc.). Refer to “Hierarchy of Controls” in the instructions sheet for more information to decide which hazard controls measures are most appropriate.

Hazardous Activity, Process, Condition, or Agent: Covid-19 pandemic
Summary of Procedure or Task: Manufacturing, assembly, testing and operations require in-person activity
Describe Hazards (Why is the procedure hazardous or what can go wrong -- what is the risk): Working in close contact with people increases exposure to Covid-19 through surfaces, air, and bodily fluids.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): The team will operate according to SCU Covid protocol on and off-campus, including wearing masks, social distancing, and frequent sanitization. We will also be sure to get tested regularly.

Hazardous Activity, Process, Condition, or Agent: Manufacturing
Summary of Procedure or Task: We plan on having to make some of the parts ourselves, and this will involve needing to cut and drill and handle machined parts. Two of our team members will have completed the Mech 101 course before starting any of the machining required in the spring quarter.
Describe Hazards (Why is the procedure hazardous or what can go wrong -- what is the risk): Machinery has the ability to injure users if used improperly, metal chips created by machine can cause injury leaving the machine causing cuts or scrapes.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): Machine Shop guidelines will be followed at all times to minimize risk (admin control). This includes: <ul style="list-style-type: none">- Use PPE Glasses Gloves Pants Shoes

- No loose clothing, hair up, closed-toed shoes, long pants, no gloves, no long sleeves, and wear safety glasses
- One person at a machine at a time
- Handle work as it is always hot and sharp
- Never use the machines alone
- Have lab manager and safety contact info
- Check vise and tools to see if they properly installed
- Use Guards when the machine is on
- Mech 101L Training

Hazardous Activity, Process, Condition, or Agent: Wiring/ Electrical Components

Summary of Procedure or Task:

The ROV runs on two parallel 16.8V Li-ion batteries onboard LiPo batteries. We will have to add an additional battery to run our appendage. We will build the control circuit separate from the existing system; it will be completely removable. This will help reduce some risk, as we will only be working with our one circuit and battery when building, adjusting and testing

Describe Hazards (Why is the procedure hazardous or what can go wrong -- what is the risk):

When working with electronics, there is risk of electrocution and damage to the electric components. There are also risks associated with the making of the circuits, such as burns due to heat guns and inhaling fumes from soldering.

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):

- Follow general safety protocols for electrical soldering
 - Safety glasses, insulated gloves if possible
- Batteries and other power sources must remain disconnected while making any changes
 - Use Safety Goggles long pants and conductive shoes
- Transport and stow LiPos in a fireproof container- special LiPo bags in ammo boxes
 - Store at 3.8 V
- Use in safe conditions (dry, clean & organized)
- Use proper steps, Lipo Safety Training (Engr 180)
 - Check for damage every time

Hazardous Activity, Process, Condition, or Agent: Mechanical Assembly (Pinch Points)

Summary of Procedure or Task:

Assembling our parts may require power tools

Describe Hazards (Why is the procedure hazardous or what can go wrong -- what is the risk):

Clothes or body parts are at risk of being caught between parts and at risk of being cut or pinched. This can also damage the parts or equipment.

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):

- PPE Glasses, Pants, Shoes (extra care to not wear loose clothes and tie long hair back, tuck strings away and have no long accessories or rings)
- Train With Power Tools and Proper Uses Mech 101L
- Only allow one person to work on ROV at a time (give space). Be aware of the people around you during assembly
- Follow assembly instructions

Hazardous Activity, Process, Condition, or Agent: Electrical Components in/near water

Summary of Procedure or Task:

There are three different cases to check: the main controls, main battery, and the additional case we are adding for appendage controls and battery.

Describe Hazards (Why is the procedure hazardous or what can go wrong -- what is the risk):

Live circuits can experience water damage or short if not properly sealed. Damage to people and the system can also occur if the control components on board get wet.

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):

- Check all seals and make sure that the electronics are safe in their waterproof cases
- PPE Pants Shoes
- Check all seals in dry conditions prior to deployment
- Recheck seals before deployment
- Don't interact with ROV while "Live"
- Announce arming so people stay back
- Leak sensors inside enclosures with electrical components.
- Watertight enclosures must be thoroughly dried off before being opened

Hazardous Activity, Process, Condition, or Agent: Arming the ROV

Summary of Procedure or Task:

A lot of our project will involve testing the existing systems and our additions to the ROV. The arm will be a metal moving part, and thrusters will spin at high speeds.

Describe Hazards (Why is the procedure hazardous or what can go wrong -- what is the risk): Interfering with motorized moving parts on the ROV can cause injury or damage the equipment. Moving parts can also trap loose hair or clothes.

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):

- PPE Gloves, Glasses, Pants, Shoes and no loose clothes (keep long hair tied back)
- Train Team on testing procedures
- Announce all tests and steps to inform by standards (“Arming ROV in 1, 2, 3...”)
- Stay away from ROV while live

Hazardous Activity, Process, Condition, or Agent: Launching and Recovering the ROV

Summary of Procedure or Task:

The ROV is heavy (100lbs+) and requires lifting on and off the edge of a boat.

Describe Hazards (Why is the procedure hazardous or what can go wrong -- what is the risk): Lifting a heavy item of the edge of a boat can result in injury or falling off the boat

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):

Lift with your legs, and use proper equipment as needed. Do not overexert yourself, and be cautious of your surroundings. Make sure that people give space.

Hazardous Activity, Process, Condition, or Agent: ROV Loss Prevention

Summary of Procedure or Task:

The ROV will be underwater out of view, at depths of up to 300ft with only one cable to send controls down.

Describe Hazards (Why is the procedure hazardous or what can go wrong -- what is the risk): The ROV can get lost if the cable or power fails. The cable can also get entangled.

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):

There must be a delegated safety person present to keep an eye on voltage levels, and the ROV will be positively buoyant, so that it will float to the surface in the event of a power failure. In addition to this, there will be a delegated person to manage the cable.

Hazardous Activity, Process, Condition, or Agent: ROV Battery

Summary of Procedure or Task:

The ROV draws power from 2 parallel LiPo batteries during its deployments.

Describe Hazards (Why is the procedure hazardous or what can go wrong -- what is the risk):

During launch, recovery and on-board transportation, these batteries are at risk of getting hot or even catching on fire, which could cause harm to the team members and the boat.

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):

- Transport and stow LiPos in a fireproof container- special LiPo bags in ammo boxes
- Store at 3.8 V
- Thoroughly check batteries before use and avoid using any damaged batteries.
- Have a fire extinguisher on board for electrical fires

Hazardous Activity, Process, Condition, or Agent: ROV Lights and Lasers for Distance

Summary of Procedure or Task:

The ROV is equipped with bright lights to see underwater, and we may also use lasers to gauge distances of objects.

Describe Hazards (Why is the procedure hazardous or what can go wrong -- what is the risk):

Shining the lights or lasers into people's eyes can hurt

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):

- The lights will be kept off as much as possible until the ROV is deployed.
- Lasers will only be used when underwater.
- Keep pointing away from those on boat

Hazardous Activity, Process, Condition, or Agent: ROV Collision Prevention and Boat propellers

Summary of Procedure or Task:

The ROV will be in operation near the boat, especially close during launch and recovery .

Describe Hazards (Why is the procedure hazardous or what can go wrong -- what is the risk):

The ROV can collide with the boat and damage itself or the boat. There is also potential for the cable to get entangled.

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):

The ROV will be piloted with extra care, and near the surface, when near the boat, and there will be a delegated person responsible for cable management, to ensure there is not too much or too little slack.

Hazardous Activity, Process, Condition, or Agent: Boat Safety

Summary of Procedure or Task:

The ROV will need to be deployed from a boat. In addition, the boat has propellers.

Describe Hazards (Why is the procedure hazardous or what can go wrong -- what is the risk):

People can fall off, get seasick, or issues with the boat can occur (sinking, fires etc). Cables and tethers can get tangled in its propellers, which also can damage anything that meets them.

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):

We will always go out with an experienced boat driver, and carefully follow the guidelines outlined in the California DBW (includes information on life jackets and other safety measures). The boat will also be turned off when possible)

Hazardous Activity, Process, Condition, or Agent: ROV Weight

Summary of Procedure or Task:

The ROV weighs over 100 lbs and requires transportation from the RSL (will require lifting in and out of a vehicle, and on and off a boat)

Describe Hazards (Why is the procedure hazardous or what can go wrong -- what is the risk):

Back injury or other injuries can occur from lifting improperly. Fingers can get pinched, and feet crushed if the ROV is dropped.

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):
The ROV will be transported via a cart whenever possible and transported by multiple people when not. There are handlebars located on the sides of the ROV for easy gripping. Ideally, those carrying it will wear steel toed shoes, or at very least, close toed shoes, and communicate with those around them. Lifting should be done properly (with legs, not back).

ROV Component Safety

Summary of Procedure or Task:

The ROV will be moved around in between missions, and it will be stored sometimes in tight spaces.

Describe Hazards (Why is the procedure hazardous or what can go wrong -- what is the risk):

The ROV's components, especially the thrusters, may be damaged during transportation and storage. This could lead to the failure of the components damaged, and possible danger during missions like electrical shorts.

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):

Components will be checked before meetings to ensure they are in working order. Also, all components will be contained within the frame of the ROV during transportation and storage to better protect all components

Li-ion Battery Disposal

Summary of Procedure or Task:

The ROV and appendage use Li-Ion batteries.

Describe Hazards (Why is the procedure hazardous or what can go wrong -- what is the risk):

Lithium-ion batteries can retain charge even after it has been damaged or has died. Due to the possibility of the battery still holding a charge even after it has been damaged or has died, it is important to ensure that the battery is completely empty - i.e. when testing it the voltage reading should be at 0V. To do this, the following steps are taken:

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):

Handle the batteries carefully to limit the chance of damage to the batteries, but if there is damage and they need to be disposed of, they should be stored in the fire cabinet for dead batteries so that EHS can properly dispose of them.

SAFETY EQUIPMENT and PPE

Select the appropriate PPE and safety supplies you will need for the project (Check all that apply)

- Appropriate street clothing (long pants, closed-toed shoes)
- Gloves; indicate type: Work
- Safety glasses/ goggles
- Face shield and goggles
- Lab coat
- Hearing protection
- Fire extinguisher
- Eyewash/safety shower
- Spill kit
- Other (list):

TRAINING REQUIREMENTS




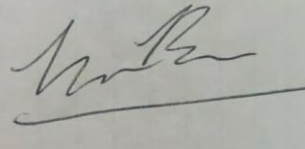
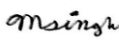
Identify the appropriate training (check all that apply)

- Biology & Bioengineering Lab Safety Camino Course – contact Lab Manager or EHS to enroll
- Chemistry & Biochemistry Lab Safety Camino Course – contact Lab Manager or EHS to enroll
 - Electrical Safety for Engineering Camino Course – contact EHS to enroll
 - LiPo Battery Safety Training – contact MAKER Lab to enroll
- Review of SDS for chemicals involved in project – access SDS library at: rms.unlv.edu/msds/
 - Laboratory Specific Training – contact Lab/Shop Owner
- Project Specific Training – contact Project Advisor
- Other (describe below):

ACKNOWLEDGEMENT

By signing, I verify that:

- 1) I am aware of the hazards and risks of all the tasks associated with the project
- 2) I have received, or will receive all the necessary safety training and/or have read the safety manual and safety data sheets (SDSs) relevant to the project before performing any hazardous tasks
- 3) I will follow all required safety precautions while working on this project, including but not limited to use of engineering controls, following safe work practices, and wearing appropriate personal protective equipment

Name of Project Team Member	Signature	Date
Kekoa Blair		11/6/21
Valeriya Chulyukina		11/4/21
Noah Villar		11/6/21
Nathan Burke		11/12/21
Mandeep Singh		11/06/21

This document must be reviewed and approved by the people below before any project work can begin. A copy of the approved document must be kept where the work is being conducted

Faculty Advisor

Name: Prof. Chris Kitts

Department: Mechanical
Engineering

Signature



Date

11/16/21

Department Chair

Name Prof. Hohyun Lee

Signature

Date

Laboratory Director/Manager

Name

Signature

Date

EH&S

Name

Signature

Date

Other

Name

Signature

Date

Appendix D: Calculations

Storage System Calculations

Granite is common at lake tahoe

↳ granite density, $\rho_g \approx 2.75 \text{ g/cm}^3 \approx 0.099 \text{ lb/in}^3$

our maximum rock sample should be $2" \times 2" \times 2" \rightarrow 8 \text{ in}^3$

so our maximum rock sample weight will be ...

$$\approx 0.099 \frac{\text{lb}}{\text{in}^3} \times 8 \text{ in}^3 = 0.792 \text{ lb}$$

if FDS of 2, do calcs w/ $\approx 1.6 \text{ lb}$ rock samples

If sediment, $\rho_s \approx 0.058 \text{ lb/in}^3$ fills the volume of the claw (13.5 in^3) then the maximum sediment sample will weigh $\approx 0.058 \frac{\text{lb}}{\text{in}^3} \times 13.5 \text{ in}^3 = 0.78 \text{ lb}$

if FDS of 2, do calcs w/ $\approx 1.6 \text{ lb}$ sediment samples

Figure D.1: Initial Load Calculations

Sample Storage

(No FEA)

3 samples of 1.6lb each
 + cake tin (0.55lb)
 + assume full of water too
 $\hookrightarrow (\pi r^2 h)(0.036 \text{ lb}/\text{ft}^3) = 8.51 \text{ lb}$
 $\approx 9 \text{ lb min w/ 0 samples}$

Note: Gear 1 (G1) driven by servo

with 3 samples of 13.5 in³;
 195.117 in³ water + (40.5 in³ of rock / sediment + 2 FOS) samples + cake tin
 $= 7.02 \text{ lb} + 4.698 \text{ lb} + 0.55 \text{ lb} = 12.268$
 $\approx 12.5 \text{ lb max w/ 3 samples}$

Gear Ratio:
 $\frac{360^\circ}{148^\circ} \approx 2.43 \approx 2.5 \text{ to standardize}$

max angle that our servo can turn $\rightarrow 148^\circ$

Servo Torque:
 $40302 \text{ in} @ 7.4 \text{ V} = \tau_0$

$\tau = \frac{\tau_0}{2.5}$
 τ_0 : torque from servo
 τ : torque experienced by sampler

$\tau = \frac{40302 \text{ in}}{6R} = \frac{25.21 \text{ bin}}{2.5} = 10.1 \text{ bin}$

Moment of Inertia (for solid cylinder) $I = \frac{1}{2} MR^2$
 $I_{\text{min}} = \frac{1}{2} (9 \text{ lb}) (5 \text{ in})^2 = 112.5 \text{ bin}^2$

$I_{\text{max}} = \frac{1}{2} (12.5 \text{ lb}) (5 \text{ in})^2 = 156.25 \text{ bin}^2$

Angular Acceleration $\alpha = \frac{\tau}{I}$
 $\alpha_{\text{min}} = \frac{10.1 \text{ bin}}{112.5 \text{ bin}^2} = 0.089 \text{ rad/s}^2$

$\alpha_{\text{max}} = \frac{10.1 \text{ bin}}{156.25 \text{ bin}^2} = 0.064 \text{ rad/s}^2$

The speed for the servo is given as 0.12 s/60 deg \rightarrow
 our calcs indicate it will reach this speed in 0.0021 s at most.
 (~1.2 min to do 360°)

Figure D.2: Storage System Gear Ratio and Torque Calculations

This just shows that the torque of the servo will still be capable of getting the loaded sample holder up to speed, and that it will take 18s.

Subsystems FEA

Cross sectional Area

$$A_c = 0.3'' * (0.5'' - 0.25'') = 0.075 \text{ in}^2$$

↑
holes create
stress concentrations

stress (from max potential torque)

servo spec $\rightarrow 29 \text{ kgcm} \approx 25.17 \text{ lbf in}$

$$M = F * d$$

$$25.17 \text{ lbf in} = F * 1.5 \text{ in} = 16.78 \text{ lbf}$$

Max Shear Experienced by Part

$$\tau = \frac{F}{A_c} = \frac{16.78 \text{ lbf}}{0.075 \text{ in}^2} = 223.73 \text{ psi} \approx 1.5 * 10^6 \text{ N/m}^2$$

↑
seen in
FEA
model

yield strengths of materials of Interest

6061 Al $\approx 35 \text{ kpsi}$ \rightarrow FOS: 156 ^{yield}

ABS $\approx 7.7 \text{ kpsi}$ \rightarrow FOS: 34

PLA $\approx 4.750 \text{ psi}$ \rightarrow FOS: 21

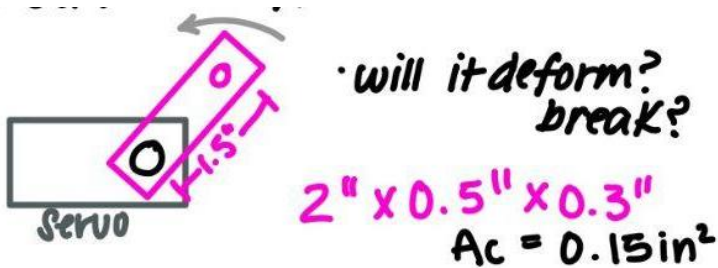


Figure D.3: Servo Horn Stress Calculation

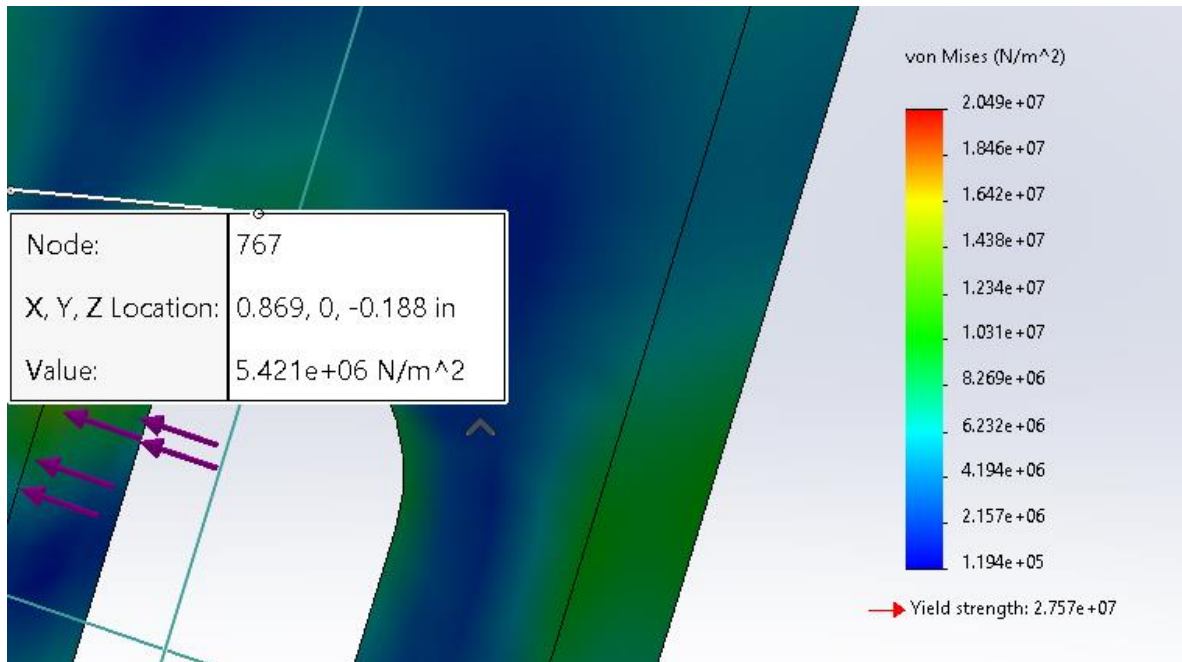
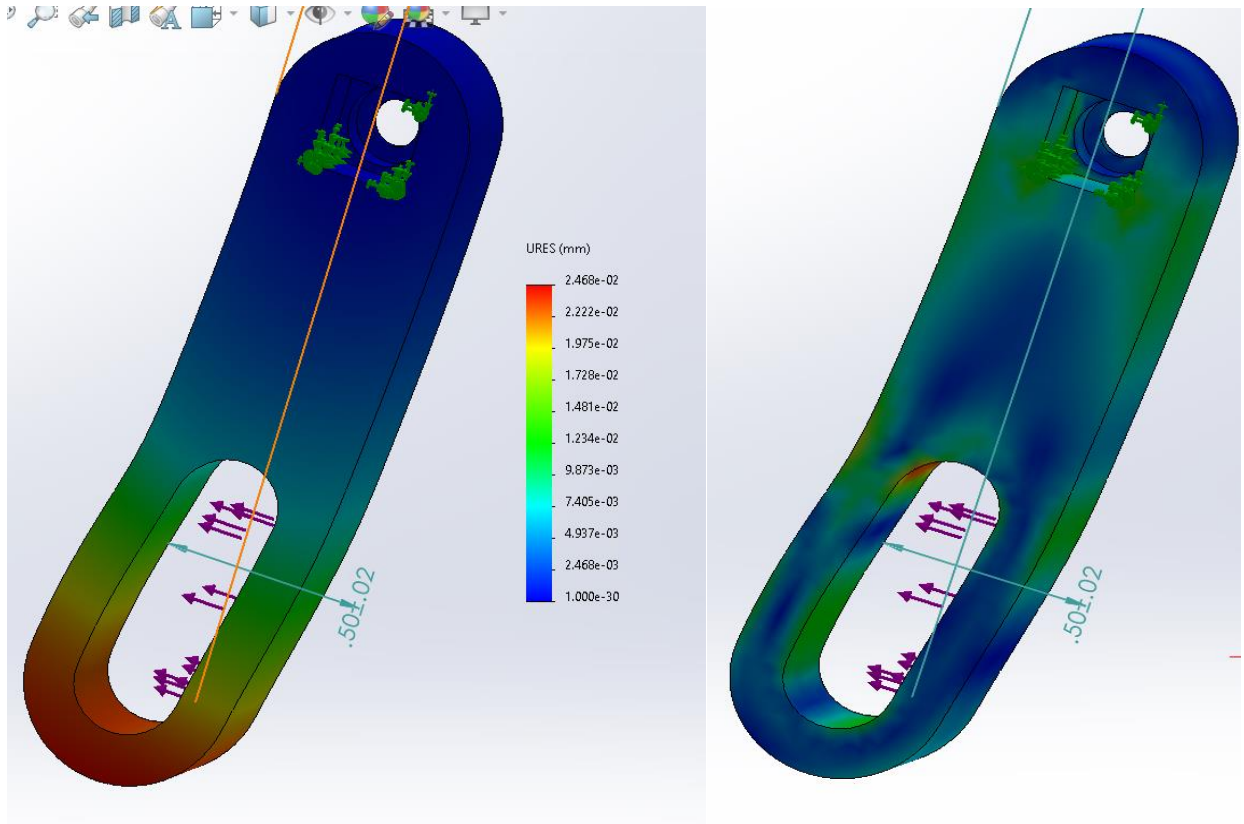
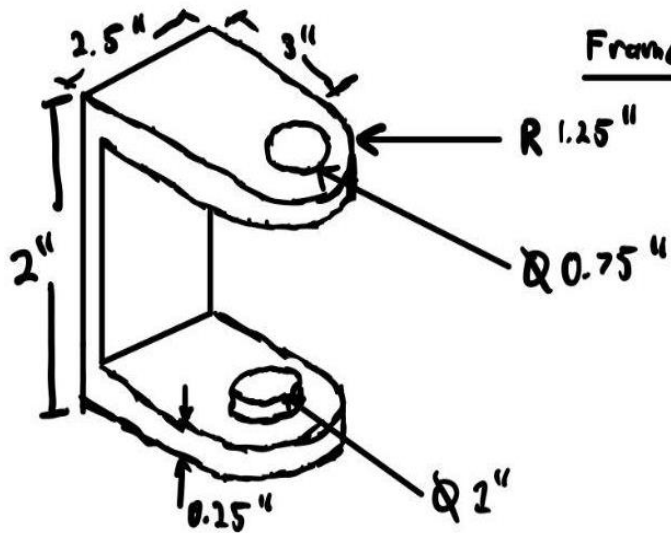


Figure D.4: Servo Horn Stress Analysis for 75N Load in Solidworks

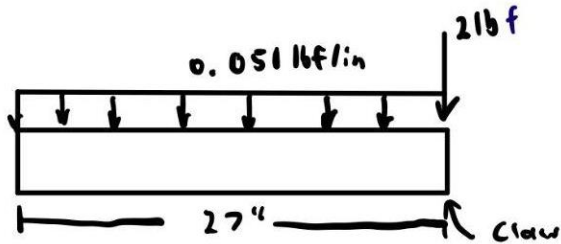


Assumptions:

1. Part is solidly fixed to the frame
2. Mass of the part itself is negligible in calculation
3. Applied force by extended/retracted arm is represented by a single bending moment

Figure D.5: Frame bracket stress calculation- dimensions and assumptions

Calculation of M :



$$1 \text{ lbf} = 32.174 \text{ lbf} \cdot \text{ft} / \text{s}^2$$

Arm sections : 0.94 lbf

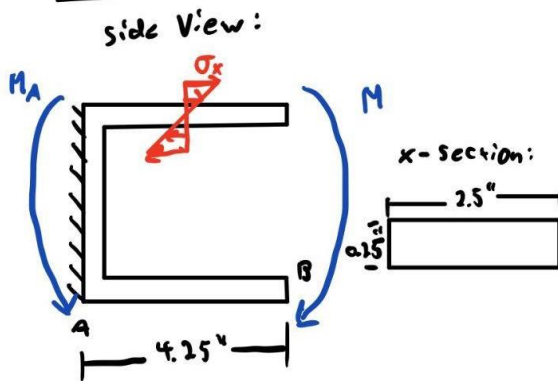
Servos : 3 · 0.143316 f = 0.4316 f

$$M = (1.37116)(13.5") + (216)(27") = \boxed{72.5 \text{ lbf} \cdot \text{in.}}$$

Assumptions:

1. Collected sample is a point load
2. Weight of Arm sections and servos are evenly distributed

WHEN CLAW IS EXTENDED FORWARD



$$\sigma_x = \frac{My}{I} \quad y = 0.0125"$$

$$I = \frac{1}{12} bh^3 = \frac{(2.5)(0.25)^3}{12}$$

$$= 3.26 \times 10^{-3} \text{ in.}^4$$

$$\sigma_x = \frac{(72.5)(0.125)}{3.26 \times 10^{-3} \text{ in.}^4}$$

$$= 2764 \text{ psi}$$

Figure D.6: Frame bracket stress calculations when claw is extended forward. From the top calculation shown above, the moment applied in the bottom calculation is 72.5 lbf-in.

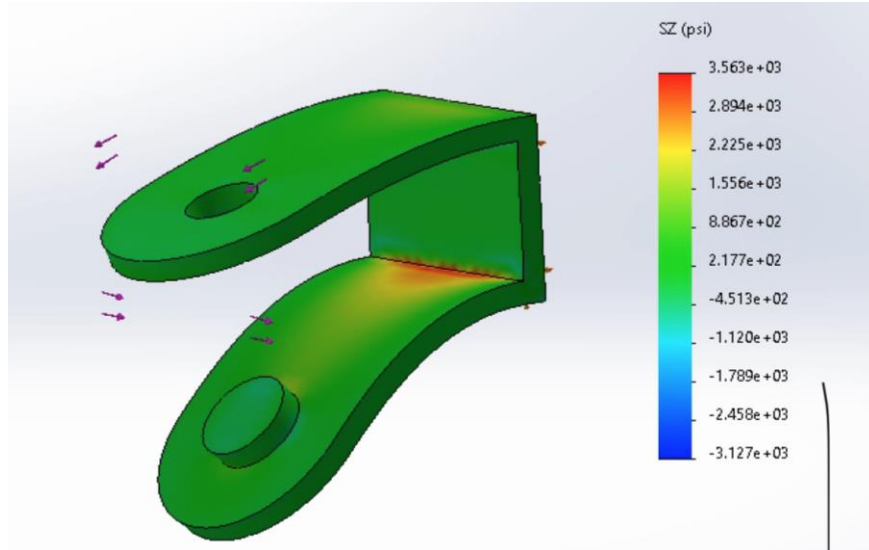


Figure D.7: Frame bracket stress analysis in Solidworks when claw is extended forward. The applied moment load, denoted by the purple arrows, is 72.5 lbf-in.

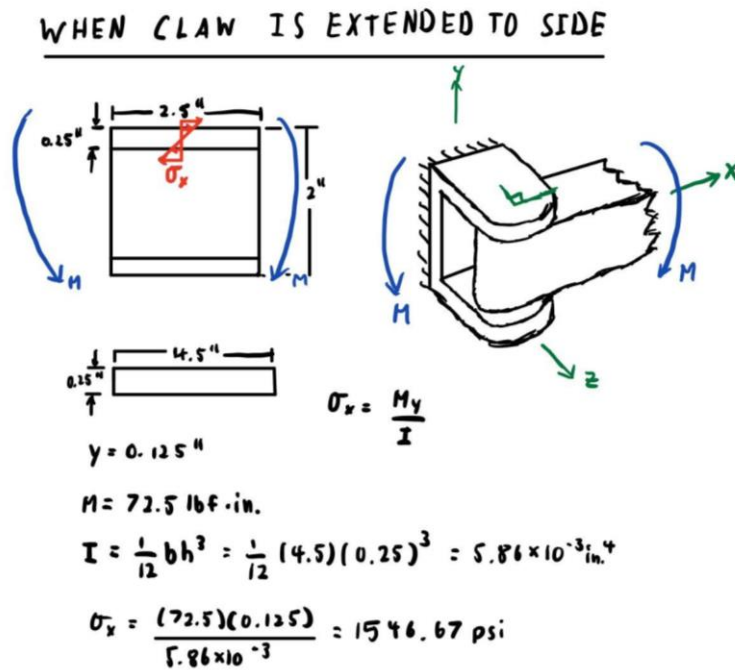


Figure D.8: Frame bracket stress calculations when claw is extended to side. The moment applied was, once again, 72.5 lbf-in.

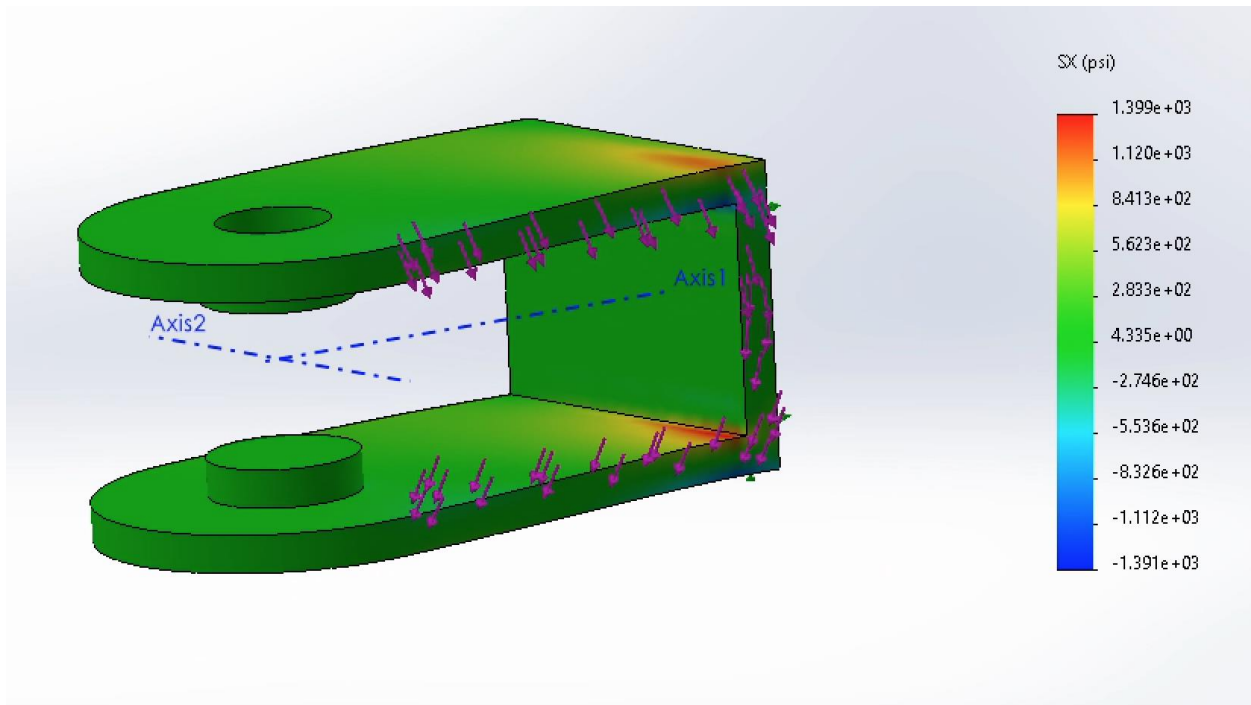


Figure D.9: Frame bracket stress analysis in Solidworks when claw is extended to the side. The applied moment load, denoted by the purple arrows, is 72.5 lbf-in.

Iterations

Normal

Factor of safety ≥ 2

$\sigma_y = 3775.1 \text{ psi (PLA)}$

$\sigma_y = 6526.7 \text{ psi (Acrylic)}$

$$F_s = \frac{3775.1}{2784} = 1.36 < 2 \times$$

PLA

$$F_s = \frac{6526.7}{2784} = 2.34 > 2 \checkmark$$

acrylic

90°

Factor of safety ≥ 2

$\sigma_y = 6526.7 \text{ (acrylic)}$

$\sigma_y = 3775.1 \text{ (PLA)}$

$$F_s = \frac{3775.1}{1546.67} = 2.44 > 2 \checkmark$$

PLA

$$F_s = \frac{6526.7 \text{ psi}}{1546.67 \text{ psi}} = 4.22 > 2 \checkmark$$

acrylic

Figure D.10: Frame bracket stress checked against PLA and acrylic material types.

Buoyancy Calculations

Servo Torque

Claw Attachment
Weights

$$W_A = W - F_B \quad W_A = (\rho_o - \rho_w) V g_c$$

$$F_B = \rho_w V g_c$$

$$W = \rho_o V g_c$$

$$W_A = \rho_o V g_c - \rho_w V g_c$$

$$W_S = 0.1433 \text{ lb} \quad g_c = 32.2 \frac{\text{ft}}{\text{s}^2}$$

$$\rho_{\text{PETG}} = 2.39 \text{ slug/ft}^3$$

$$\rho_{\text{acrylic}} = 2.31 \text{ slug/ft}^3$$

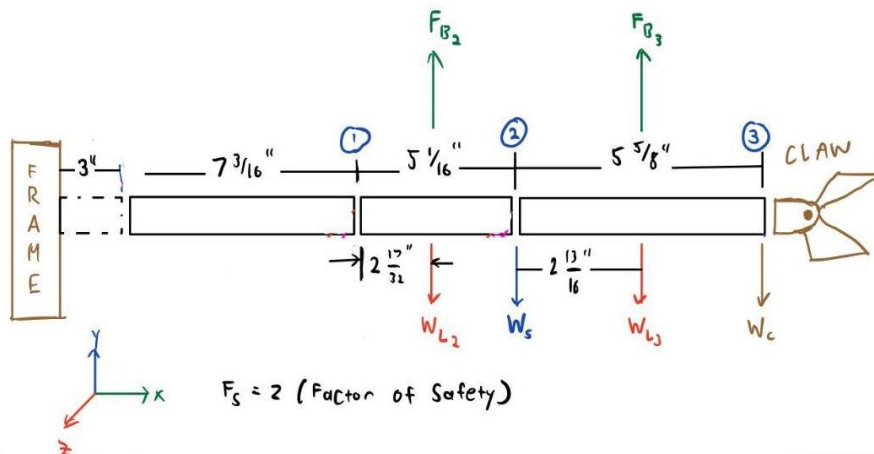
$$\rho_w = 1.94 \text{ slug/ft}^3$$

$$W_{L_2} = (2.31 - 1.94)(0.00069)(32.2) + 2[(2.31 - 1.94)(0.00131)(32.2)] + 2[(2.39 - 1.94)(0.0018)(32.2)] = 0.0915 \text{ lb}$$

$$W_{L_3} = (2.31 - 1.94)(0.00059)(32.2) + 2[(2.31 - 1.94)(0.00159)(32.2)] + (2.39 - 1.94)(0.00172)(32.2) + (2.39 - 1.94)(0.00242)(32.2) = 0.194 \text{ lb}$$

$$W_c = 0.1433 + 1.6 + 0.114 = 1.8564 \text{ lb}$$

$$F_{B_2} + F_{B_3} = 2.101 \text{ lb}$$



Max Servo Torques
(From Blue Trail Engineering):

$$M = 29.5 \text{ lb} \cdot \text{in.}$$

$$M_{Fr} = 14.75 \text{ lb} \cdot \text{in.}$$

$$F_{B_3} = 0.751 \text{ lb}$$

$$V_3 = \frac{0.75}{0.0242} = 30.99 \text{ in.}^3$$

$$F_{B_2} = 0.4125 \text{ lb}$$

$$V_2 = \frac{0.4125}{0.0242} = 17.04 \text{ in.}^3$$

$$\frac{F_B}{V} = \frac{2.101 \text{ lb}}{72 \text{ in.}^3} = 0.0292 \text{ lb/in.}^3$$

② :

$$14.75 = W_c (5.625) + W_{L3} (2.8125) - F_{B3} (2.8125)$$

$$F_{B3} = -1.42 \text{ lb} \quad \text{FOAM NOT NEEDED}$$

① :

0 for 1st iteration

$$14.75 = W_c (10.6875) + W_{L3} (7.875) - F_{B3} (7.875) + W_s (5.0625) + W_{L2} (2.53125)$$

$$- F_{B2} (2.53125)$$

$$F_{B2} + F_{B3} = 2.10 \text{ lb}$$

$$\text{when } F_{B3} = 0 \rightarrow F_{B2} = 2.74 \quad \text{check}$$

$$2.74 + 0 = 2.74 \text{ lb } \times$$

$$\text{when } F_{B3} = 0.5 \text{ lb} \rightarrow F_{B2} = 1.19 \text{ lb}$$

$$1.19 + 0.5 = 1.69 \text{ lb } \checkmark$$

$$\text{when } F_{B3} = 0.75 \text{ lb} \rightarrow F_{B2} = 0.4125 \text{ lb}$$

$$0.75 + 0.4125 = 1.1625 \text{ lb } \checkmark$$

$$2 \cdot \left[2.68 \cdot \left(0.75 - \frac{0.25}{2} \right) \cdot 1.5 \right] = 5.025 \text{ in.}^3$$

$$20.7 = 7.78 \cdot 1.5 \cdot H_1$$

$$H_1 = 1.77 \text{ in.} \quad 0.9'' \text{ on each side}$$

Blocks Needed for F_{B3}

$$2 \times 2.68'' \times 1.5'' \times 0.625''$$

$$2 \times 7.78'' \times 1.5'' \times 0.9''$$

Blocks Needed for F_{B2}

$$2 \cdot [W - 1.5 \cdot 0.625] = 4.38 \text{ in.}$$

$$2 \times 2.13'' \times 1.5'' \times 0.625''$$

$$9.75 = 6.5 \cdot 1.5 \cdot l \quad W = 2.13''$$

$$2 \times 6.5'' \times 1.5'' \times 0.5''$$

Figure D.11: Arm buoyancy calculations to determine foam required for proper function

Appendix E: Budget and BOM

[Link to BOM and Budget Tracking Sheet](#)

Note: Many parts have zero cost because they were made using scrap parts (ie. delrin and acrylic as well as some aluminum tubing) or made using 3-D printing which we have unlimited free access to on campus for class related work.

	A	B	C	D	E	F	G	H	I
1	Assembly	Part	Manufacturing	Description	Cost Per Part <i>(estimates italics)</i>	Quantity	Total Cost	Type of Funding	Status
2	Claw	Waterproof Servo	Bought	Power Unit	\$381.99	1	\$381.99	School of Engineering	Requested in Quartzzy 1/21, Ordered 1/25, Recieved 2/3
3		Frame	PLA 3D	Connector for all parts	\$0.00	1	\$0.00	Maker Lab	Design in Progress - to be prototyped by 2/28
4		Piston	PLA 3D	Linear Power	\$0.00	1	\$0.00	Maker Lab	Design in Progress - to be prototyped by 2/28
5		Horn	Aluminum Machined	Rotating Arm	\$0.00	1	\$0.00	Machine Shop Scrap	Design in Progress - to be prototyped by 2/28
6		Connector	Aluminum Machined	Transfers Motion to Claw	\$0.00	4	\$0.00	Machine Shop Scrap	Design in Progress - to be prototyped by 2/28
7		Claw	PLA 3D	Scoops material	\$0.00	2	\$0.00	Maker Lab	Design in Progress - to be prototyped by 2/28
8		Claw Servo Mount	3-D Print	Holds Servo to frame and claw	\$0.00	1	\$0.00	Maker Lab	Being 3-D printed
10		M4x15mm hardware	Bought	Servo to Horn	\$10.00	1	\$10.00	School of Engineering	Home Depot
11		.25" Roll pins	Bought	Claw arm, horn connections	\$10.00	1	\$10.00	School of Engineering	Home Depot
14	Sample Storage	Waterproof Servo	Bought	Power Unit	\$381.99	1	\$381.99	School of Engineering	Requested in Quartzzy 1/21, Ordered 1/25, Recieved 2/3

15	Acrylic sheet (Lid)	Laser Cut	Top of cake tin to keep samples in place	\$0.00	1	\$0.00	Machine Shop Scrap (Talked to Rod Broome 1/24)	To be laser cut by 2/18
16	6061 Square Aluminum Tube 1x1"	Machine lab	20in section to cut crossbar segments from	\$0.00	1	\$0.00	School of Engineering	Received aluminum scrap from rod
17	Delrin Supports	Machine lab	So storage can rotate on its support/ reduce friction	\$0.00	1	\$0.00	Scrap in machine lab	Machine by end of quarter
18	Gears (10 and 25 teeth) & Belt	Bought	Translate limited servo motion to full turn of the storage pan	\$20.00	1	\$20.00	School of Engineering	Order ASAP
19	Cake tin	Bought	Act as main storage pan	\$13.59	1	\$13.59	School of Engineering	Requested in Quartzzy 1/21, Ordered 1/25, Received 1/30
20	Corner Bracket	Bought	Connect crossbar to main frame	\$2.00	2	\$4.00	School of Engineering	Get at Home Depot ASAP (hole 1" from corner)
21	Acrylic Separators	Laser cut	Separate the 4 storage compartments	\$0.00	1	\$0.00	Machine Shop Scrap (Talked to Rod Broome 1/24)	Laser cut by end of quarter

22	Arm	Waterproof Servo (Limited Rotation)	Bought	Power Unit	\$381.99	3	\$1,145.97	School of Engineering	Requested in Quartzzy 1/21, Ordered 1/25, Received 2/3
23		Waterproof Servo Full Turn	Bought	Power Unit for elbow joints	\$480.00	2	\$960.00	RSL	Requested in Quartzzy 2/4
24		Arm Additional Bouyancy (Foam)	Needs to be bought and cut to fit within arm	Arm is too heavy for the servos without this (will also add rigidity)	\$15.00	1	\$15.00	School of Engineering	To be bought by 2/18 and cut by 2/25
25		Servo Gear	3D Printed	Drive rotation of arm segment 1	\$0.00	1	\$0.00	Maker Lab	To be printed by 3/18
26		Gear Extension Pin	3D Printed	Connect arm segment 1 to frame fixture servo	\$0.00	1	\$0.00	Maker Lab	To be printed by 3/18
27		Bracket Connector	3D Printed	Join Top and Bottom parts of frame fixture	\$0.00	2	\$0.00	Maker Lab	To be printed by 3/18
28		Frame Connection Bracket - Back Panel	3D Printed	Secure frame fixture to the existing Nautilus Frame	\$0.00	1	\$0.00	Maker Lab	To be printed by 3/18

29	Arm Segment Servo Fixture	3D Printed	Fix each 7-turn servo to each arm segment	\$0.00	2	\$0.00	Maker Lab	To begin printing on 3/1
30	Arm Segment Servo Connector	3D Printed	Connect arm segment 2 to the two arm servos	\$0.00	2	\$0.00	Maker Lab	To be printed by 3/18
31	Claw Attachment	3D Printed	Connect arm segment 3 to claw sub assembly	\$0.00	1	\$0.00	Maker Lab	To be printed by 3/18
32	Frame Connection Bracket - Top	3D Printed	Join arm assembly to the existing Nautilus frame	\$0.00	1	\$0.00	Maker Lab	To be printed by 3/18
33	Frame Connection Bracket - Bottom	3D Printed	Join arm assembly to the existing Nautilus frame	\$0.00	1	\$0.00	Maker Lab	To be printed by 3/18
34	Arm Segment #1 - Top Panel	Laser cut from Acrylic	Provide structure of the arm segment by which the servos are attached	\$0.00	1	\$0.00	Maker Lab	To be cut by 3/18
35	Arm Segment #1 - Bottom Panel	Laser cut from Acrylic	Provide structure of the arm segment by which the	\$0.00	1	\$0.00	Maker Lab	To be cut by 3/18

36	Arm Segment #1 - Vertical Panel	Laser cut from Acrylic	Provide structure of the arm segment by which the servos are attached	\$0.00	1	\$0.00	Maker Lab	To be cut by 3/18
37	Arm Segment #2 - Top/Bottom Panel	Laser cut from Acrylic	Provide structure of the arm segment by which the servos are attached	\$0.00	2	\$0.00	Maker Lab	To be cut by 3/18
38	Arm Segment #2 - Vertical Panel	Laser cut from Acrylic	Provide structure of the arm segment by which the servos are attached	\$0.00	1	\$0.00	Maker Lab	To be cut by 3/18
39	Arm Segment #3 - Top/Bottom Panel	Laser cut from Acrylic	Provide structure of the arm segment by which the servos are attached	\$0.00	2	\$0.00	Maker Lab	To be cut by 3/18

39		Arm Segment #3 - Top/Bottom Panel	Laser cut from Acrylic	Provide structure of the arm segment by which the servos are attached	\$0.00	2	\$0.00	Maker Lab	To be cut by 3/18
40		Arm Segment #3 - Vertical Panel	Laser cut from Acrylic	Provide structure of the arm segment by which the servos are attached	\$0.00	1	\$0.00	Maker Lab	To be cut by 3/18
41	Controls	Controller	Bought	Control the arm separately from the ROV motion	\$16.69	1	\$16.69	School of Engineering	Requested in Quartzzy 1/20, Ordered 1/21, Received 1/24
42		4" Waterproof Tube	Bought	Store additional battery and electronics for the arm	\$177.30	1	\$177.30	School of Engineering	Requested in Quartzzy 1/21, Ordered 1/25, Received 1/30
43		Tube Attachment to Frame	Machine Shop	Hold additional arm electronics tube to the main frame and be removable	\$0.00	1	\$0.00	Machine Shop Scrap (Talked to Rod Broome)	Made 4/27

44		Plugs for Tube	Bought	Used for sealing the electronics capsule	\$5.00	9	\$45.00	School of Engineering	Will be purchased after more controls testing/ seeing how many wires we need leaving the controls tube or additional to the main tube (have some leftover from last year)
45		I2C Bus Servo Controller	Bought	Control arm servos- links to main Arduino	\$60.00	1	\$60.00	School of Engineering	Purchased and in RSL (from fall quarter)
46		14.8V Power Supply	Have	Power supply to arm	\$0.00	1	\$0.00	RSL	In RSL or Garage (should clarify which one is okay to hold onto)
47		DC-DC Step-down Buck Module	Bought		\$0.00	1	0	School of Engineering	Included in set with I2C bus
48		Cobalt series Bulkhead connector	Bought		\$48.03	5	\$240.15	RSL	Order by 2/18
49	General	Prototyping Materials	Bought/ built with scissors and hot glue	Make our arm orientation, see what is in field of view etc	\$23	1	\$23	School of Engineering	Bought and built Prototype winter week 5
50		Travel Expenses	N/A	To test sites	\$300	1	\$300	RSL	Will pay for testing

51	Miscellaneous Hardware	Bought	Screws to connect subassemblies to frame and servos to parts	\$100	1	\$100	RSL	Order as needed
52	Miscellaneous Electronics	Bought	Wires and control tube goodies	\$300	1	\$300	RSL	Order as needed
53	Cabling	Bought	Connect subassemblies servos to controls tub	\$200	1	\$200	RSL	Order as needed
54	8-32 Stainless steel button screws	Bought	Connect servos to servo fixtures	\$20	1	\$20	RSL	Order as needed
55	Subsea bouyancy foam	Bought and then mac	Add bouyancy to	\$33	1	\$33	School of Engine	Requested in Quartz

Appendix F: Conference Presentation Slides



SANTA CLARA UNIVERSITY
SCHOOL OF ENGINEERING

Nautilus ROV Arm Attachment

www.scu.edu/engineering



Meet the Team



Noah Villar

Mechanical Engineering



Kekoa Blair

Mechanical Engineering



Valeriya Chulyukina

Mechanical Engineering



Nathan Burke

Computer Engineering



Mandeep Singh

Computer Engineering





Advisors



Christopher Kitts

SCU Professor and Robotic
Systems Laboratory Director



Michael Neumann

SCU Professor and Robotic
Systems Laboratory Advisor



Agenda

1. Background and Motivation
2. Project Summary
3. Stakeholder Requirements
4. Intended System Function
5. Subsystems
6. Testing and Results





Background & Motivation

Over 70% of the Earth's surface is covered by water

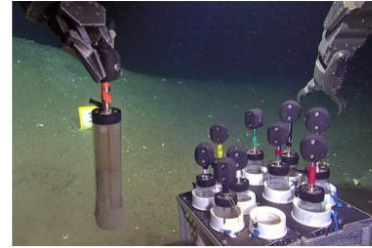


Eurythenes plasticus

A species so deep underwater people only recently discovered it- and it contains microplastics!



Underwater research can help us to understand the past and future effects of **human actions, extreme weather and seismic events.**

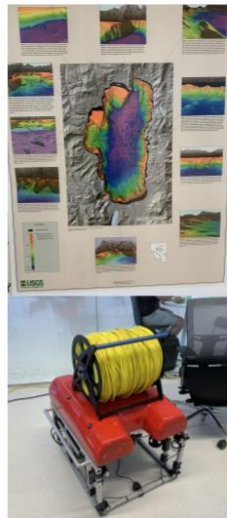


Project Summary

A Tsunami in Lake Tahoe?

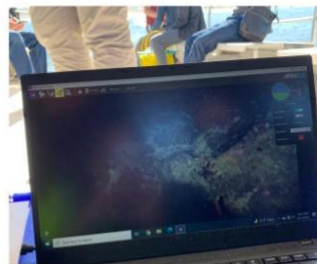


Over the past 15 years, RSL faculty, students and staff have teamed with researchers from the US Geological Survey and University of Nevada, Reno to perform robotic exploration of Lake Tahoe. This work has resulted in evidence of historic tsunami in the Lake:



Goal:

To develop a multi-degree of freedom sample taking apparatus can be created for use with SCU's Nautilus ROV





Stakeholder Requests

Stakeholders:

- Researchers (Lake Tahoe & MBARI)
- Dr. Kitts and Dr. Neumann
- Industry Experts (Dr. Wheat, and Dr. Schweickert)



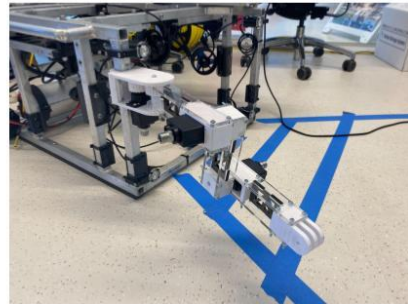
Main Requests:

- Maintain function with and without arm
- Collect and store samples
- Topside electronics safety
- Easy to use



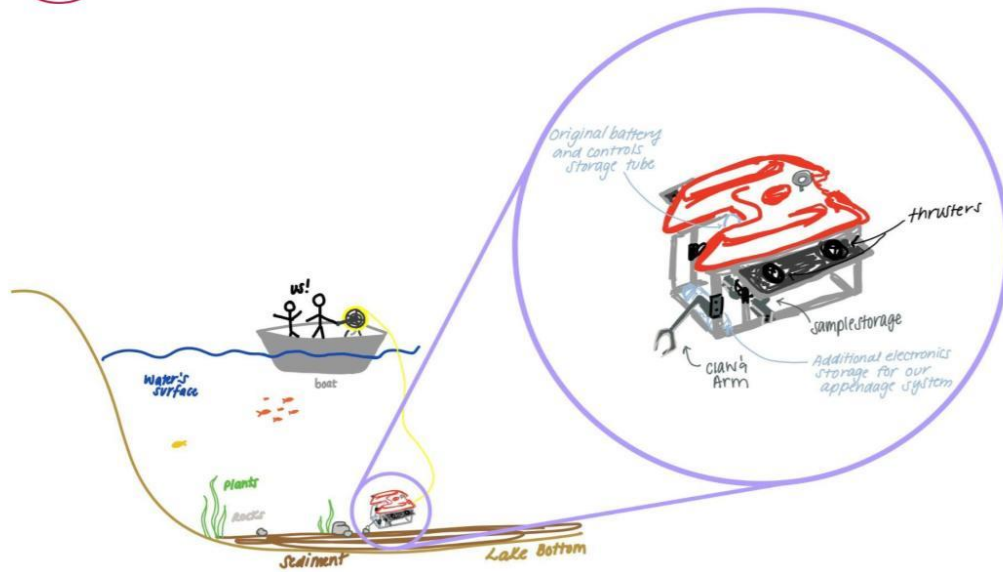
Requirements

- Collect 3 samples in 45 min deployment
- Functionally scoop and store 2 in³ of sediment
- Be able to lift 1.6 lbs underwater
- Be able to reach 80% of the width of the field of view





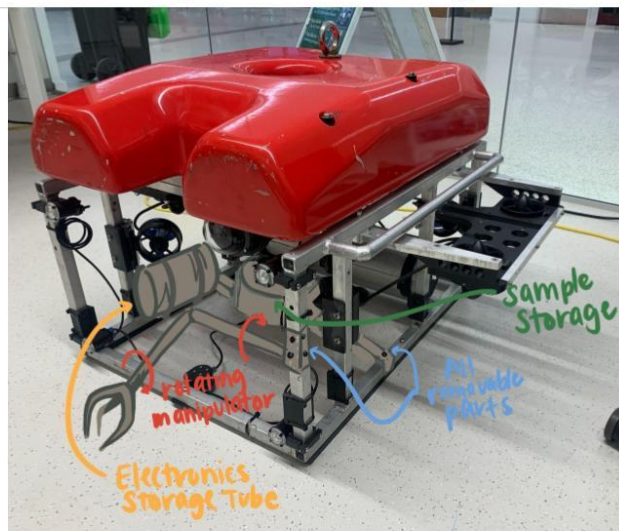
Intended System Function



9

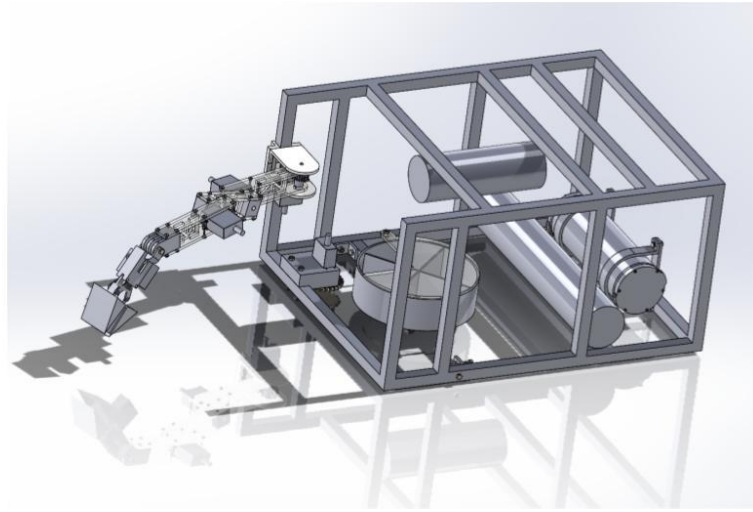


Initial Manipulator Design

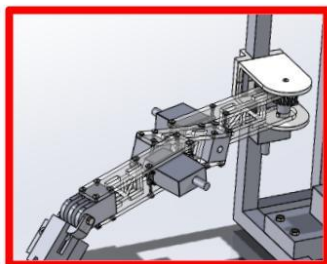




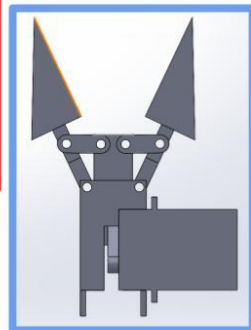
Final Manipulator Design



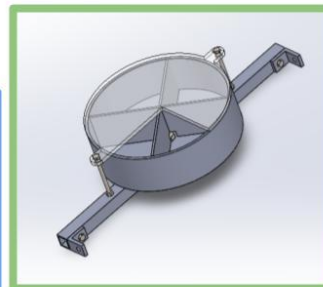
Subsystems



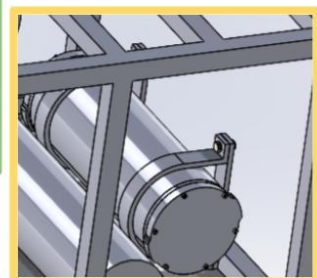
Arm



Claw



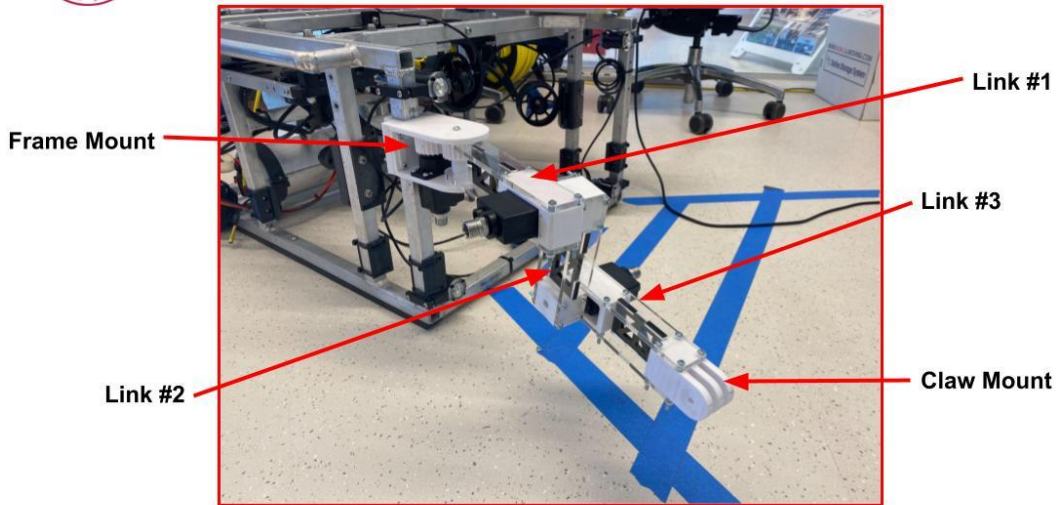
Storage Mechanism



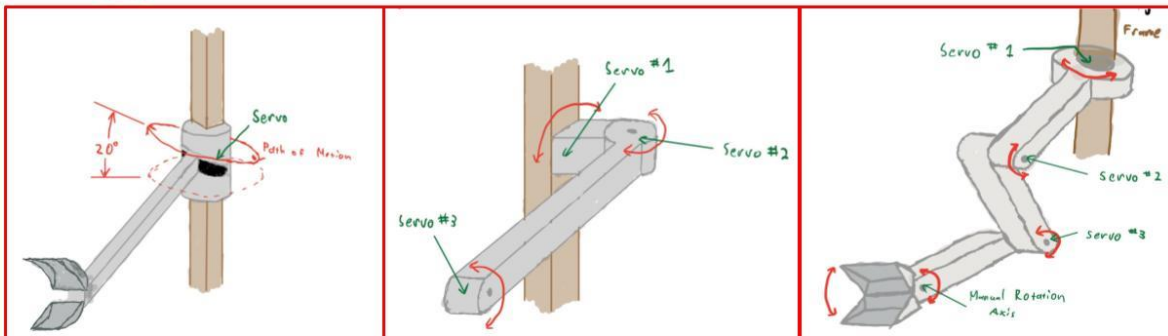
Electronics Tube & Software



Manipulator Arm



Manipulator Arm - Design Process



Design #1

- ✓ Minimalistic (1 Servo, Simple Control Protocol, Budget Friendly)
- ✗ Limited Range of Motion (1 DOF)

Design #2

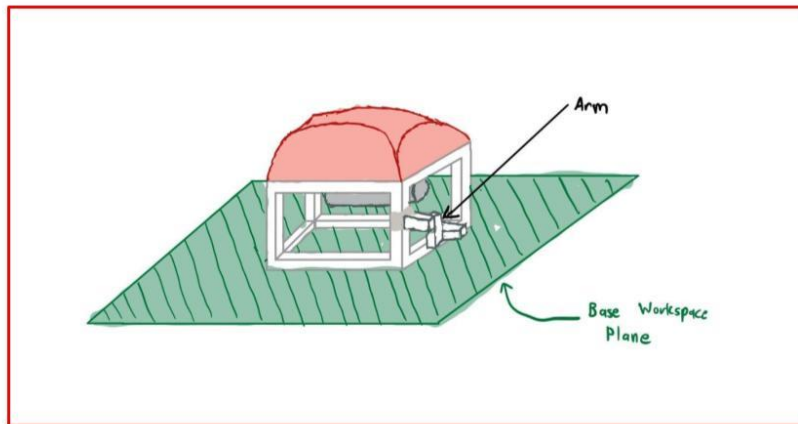
- ✓ Motion Capabilities (2 DOF)
- ✗ Stiff Movement (1 Major Link, Not Extendable)

Design #3

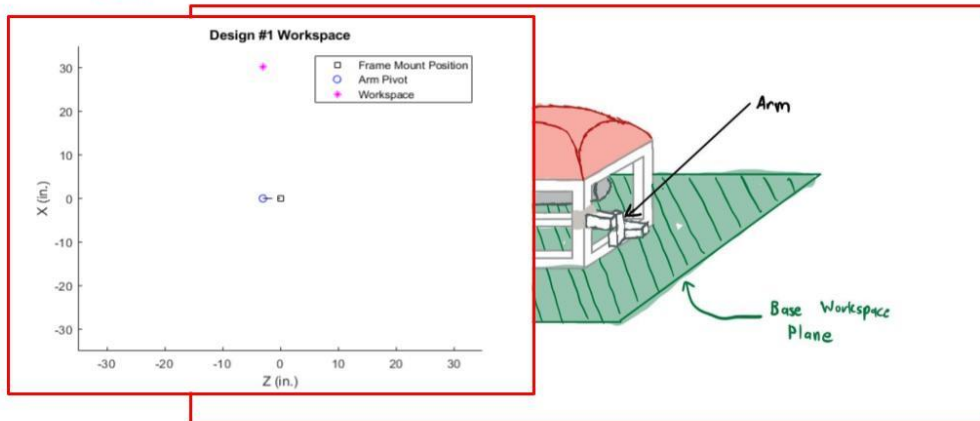
- ✓ Versatile Motion Capabilities (3 DOF, Telescoping motion)
- ✗ Complex User Control
- ✗ Weight (More parts req.)



Manipulator Arm - Range of Motion

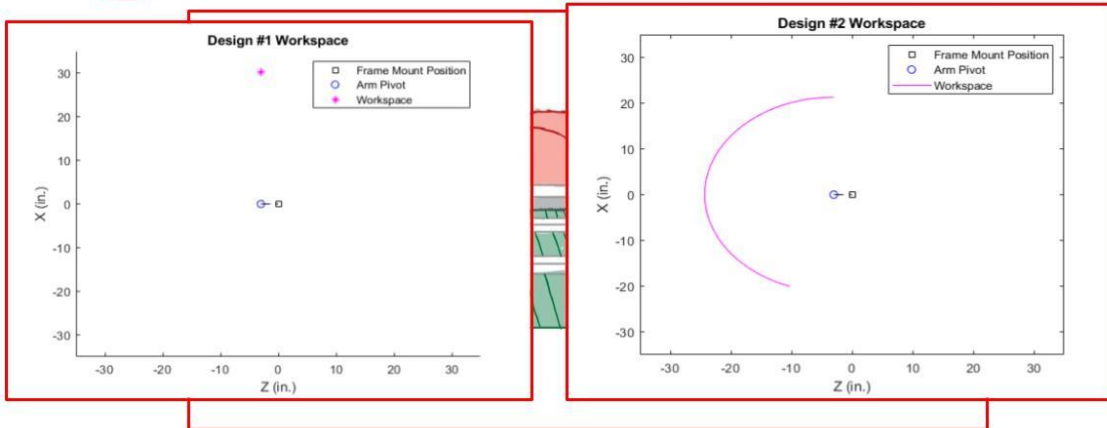


Manipulator Arm - Range of Motion

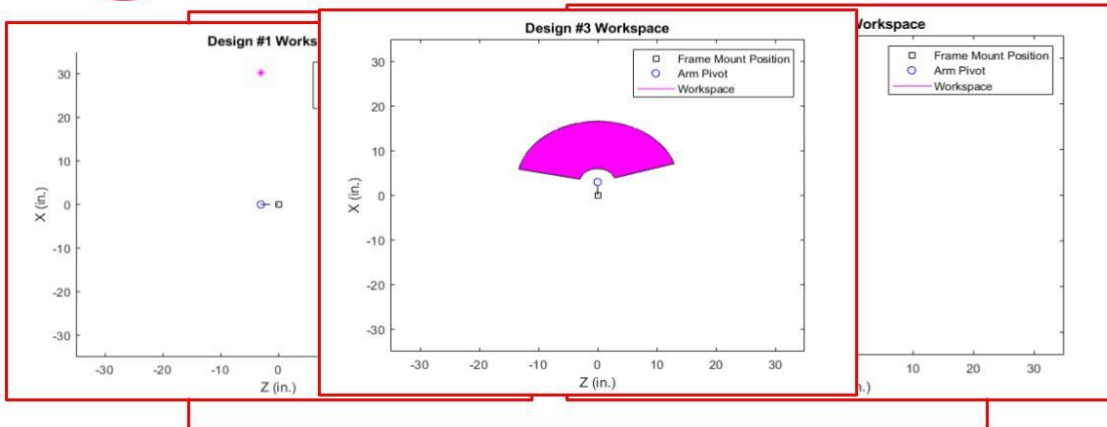




Manipulator Arm - Range of Motion

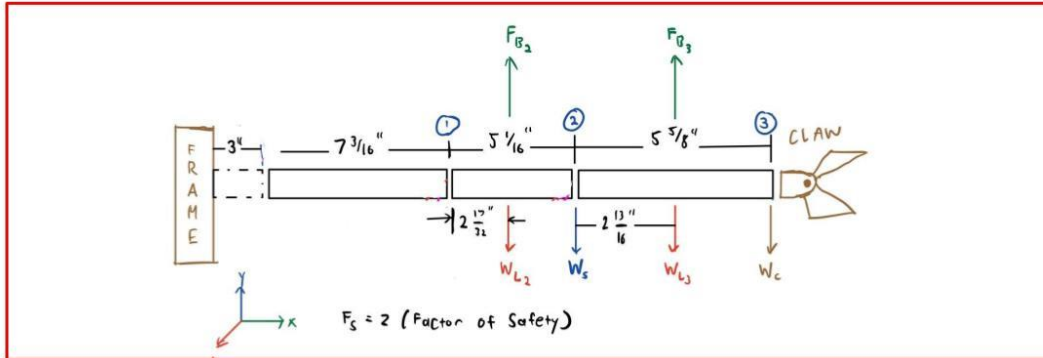


Manipulator Arm - Range of Motion

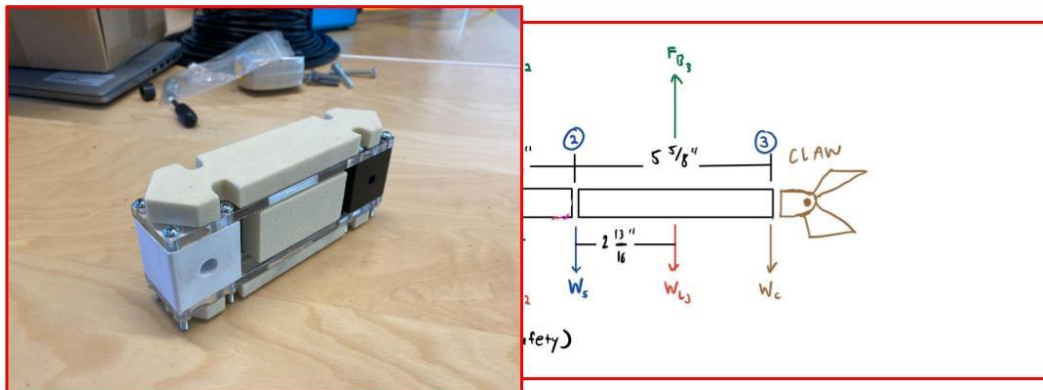




Manipulator Arm - Buoyancy

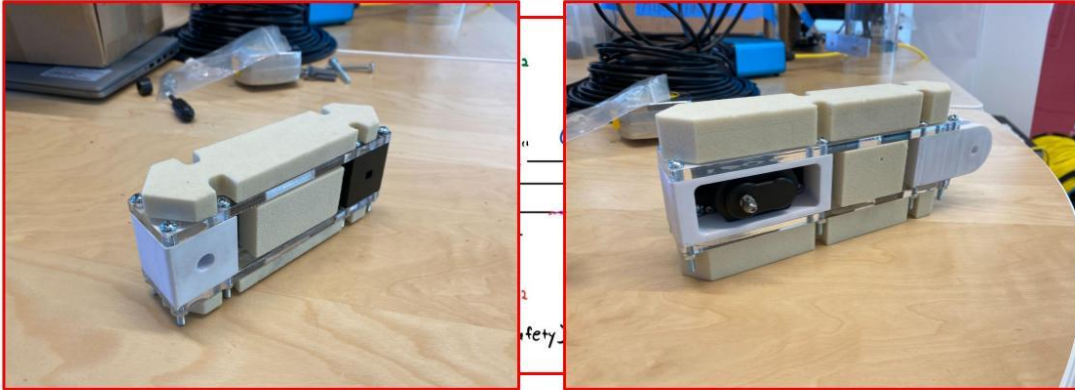


Manipulator Arm - Buoyancy



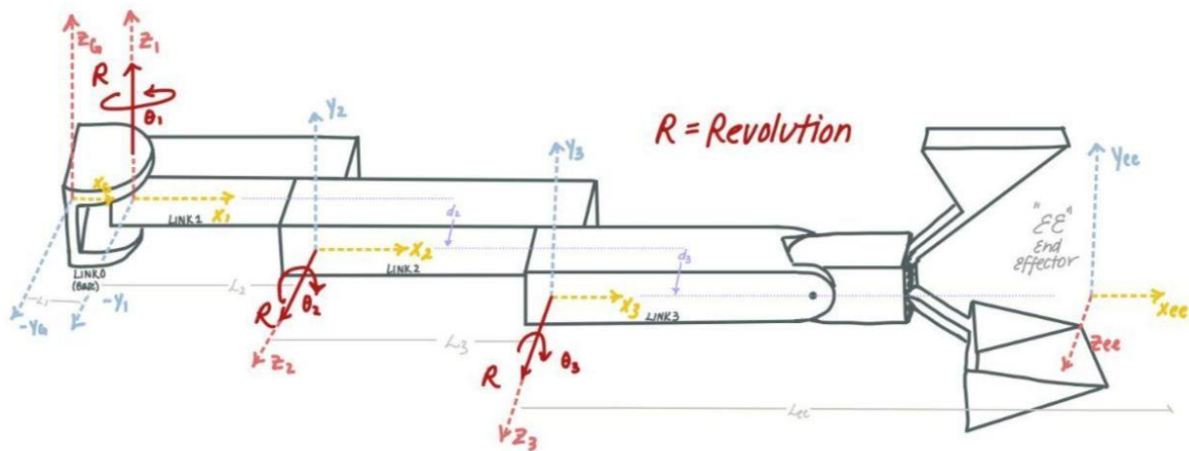


Manipulator Arm - Buoyancy



Manipulator Arm - Kinematic Analysis

Serial Chain Manipulator Kinematics: Joint Angles \longleftrightarrow End Effector Position



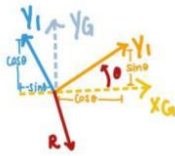


Manipulator Arm - Kinematic Analysis

Denavit-Hartenberg Parameters (DH Parameters)

Standard method to write kinematic equations of a manipulator

- z axis is axis of rotation
- x axis must be perpendicular to current and previous z axis
- rotational matrices
- homogeneous transform
- convert rotational velocity to translational velocity
- MATLAB robotics toolbox



$${}^0T_1 {}^1T_2 {}^2T_{ee} = {}^0T_{ee}$$

$${}^G_1T = \begin{bmatrix} ({}^G_0\hat{x}) & ({}^G_0\hat{y}) \\ 0 & 0 \end{bmatrix}$$

$${}^G_1T = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

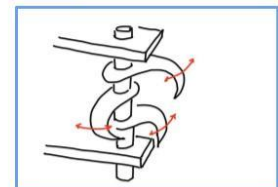
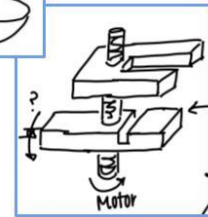
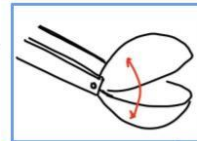
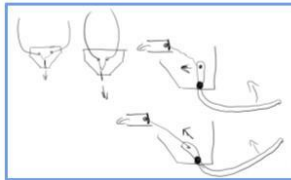
$$\dot{x} = J\dot{\theta}$$

$$\dot{\theta} = J^{-1}\dot{x}$$

Link Length: a	Link Twist: α	Link Offset: d	Joint Angle: θ
L1= 3"	0	0	θ_1
L2= 7 3/16"	-90	1.5"	θ_2
L3= 5 1/16"	0	1.5"	θ_3
EE= 13 7/8"	0	0	θ_{ee}

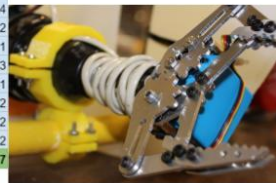


Claw Design Matrix



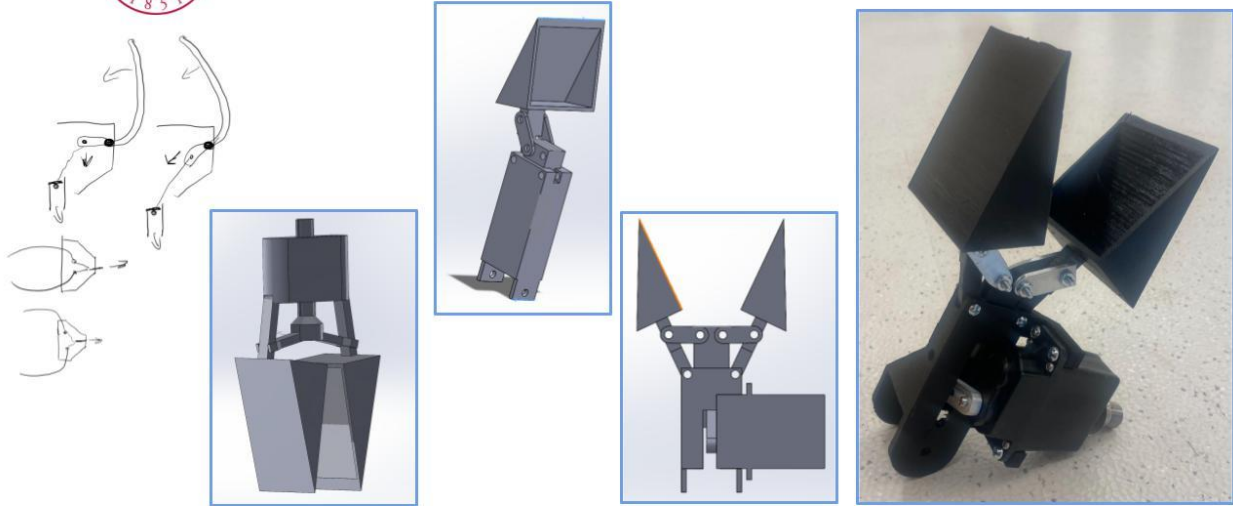
Claw Design					
	Importance (weight)	Clam	Three Prong	Screw Jaw	Two Prong
Compatibility with Existing Tools	0.5	4	4	2	1
Cost	0.3	2	4	3	1
Manufacturability	0.7	2	3	2	4
Manipulation Ability	1	2	4	1	2
Range of motion	0.7	2	2	1	1
Weight	0.4	2	2	2	3
Size	0.6	4	2	3	1
Can collect rocks	0.8	3	3	1	2
Ability to break off thin rock layers	0.3	2	3	1	2
Maneuverability/ Ease of use	0.8	3	3	1	2
Total Weighted Score		13	15.1	8.4	9.7

* Each ranked on a scale of 1-4





Claw Design & Iteration



Claw Analysis

Horn FEA Calc

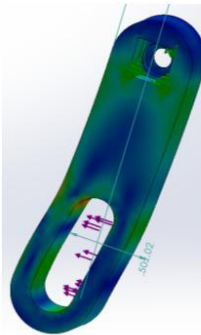
Servo spec: max torque 29 kg cm
~ 2.048 ft lb

Cross sectional area - $A = .3 \cdot .25 = .075 \text{ in}^2$

Stress - $M = F \cdot d$
 $2.048 = \frac{1.6}{12} \cdot X$
 $F = 16.784 \text{ lb}$

Shear - $\tau = \frac{F}{A} = \frac{16.784 \text{ lb}}{.075 \text{ in}^2} = 223.736 \text{ PSI}$

Shear strength - $Al = 30 \text{ kPSI}$ FOS = 134.06
 $ABS = 7700 \text{ PSI}$ FOS = 34.40
 $PLA = 4750 \text{ PSI}$ FOS = 21.23



Servo n

$\frac{I}{H} \cos \theta = F$

displacement from horizontal
 force
 corrector force
 force length

Cross sectional area
 $\frac{F}{A} = \frac{F}{A}$

Claw Volume for Sediment
 $V \approx 2.3 \frac{\text{cm}^3}{\text{cm}}$

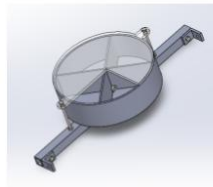
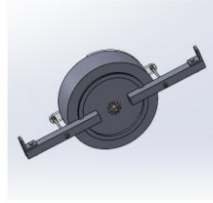
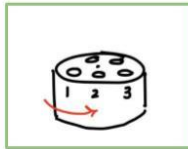
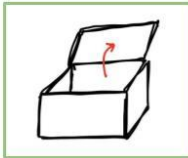
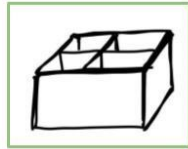
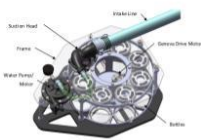
$V = h \cdot w \cdot z$

$V \approx w \cdot h \cdot \frac{z}{2}$ (cylinder)

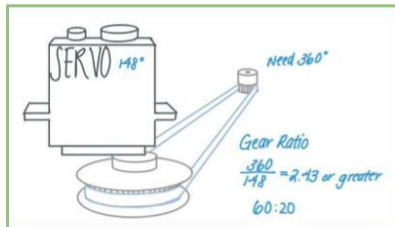
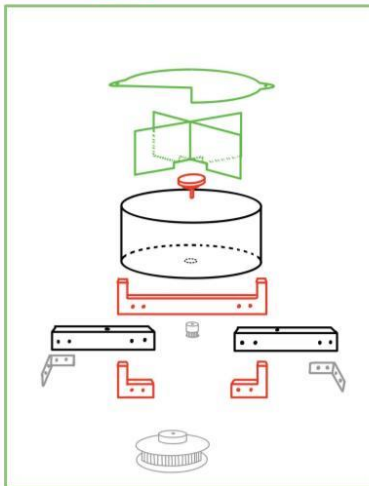
$F = (s_1 - s_2) \cdot g \cdot V = g (s_1 - s_2) \cdot w \cdot h \cdot z \approx 9.81 \text{ (ft/sec}^2) \cdot \frac{3.3 \cdot 1.5}{2} \cdot \left(\frac{.075 \text{ in}^2}{.25 \text{ in}}\right) = 2.82 \text{ N}$
 force for claw assuming claw rental keyway
 ~ 287 kg



Storage System



Storage System

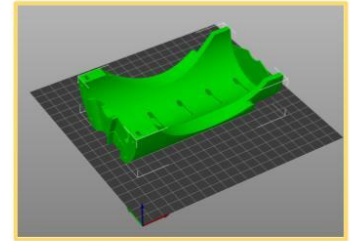
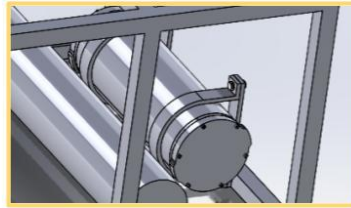
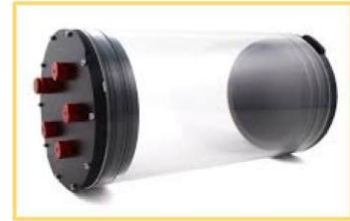




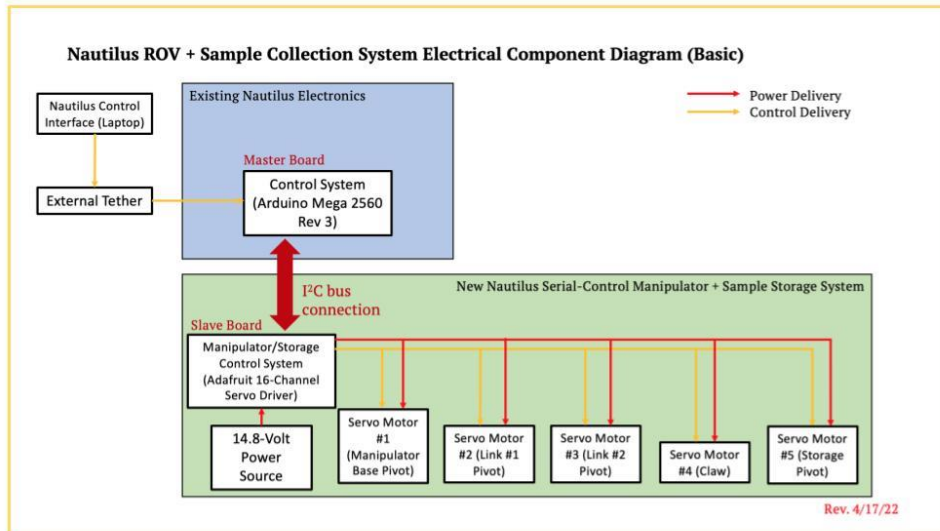
Electronics Tube



Separate acrylic tube contains the battery and controls for the sample taking system.

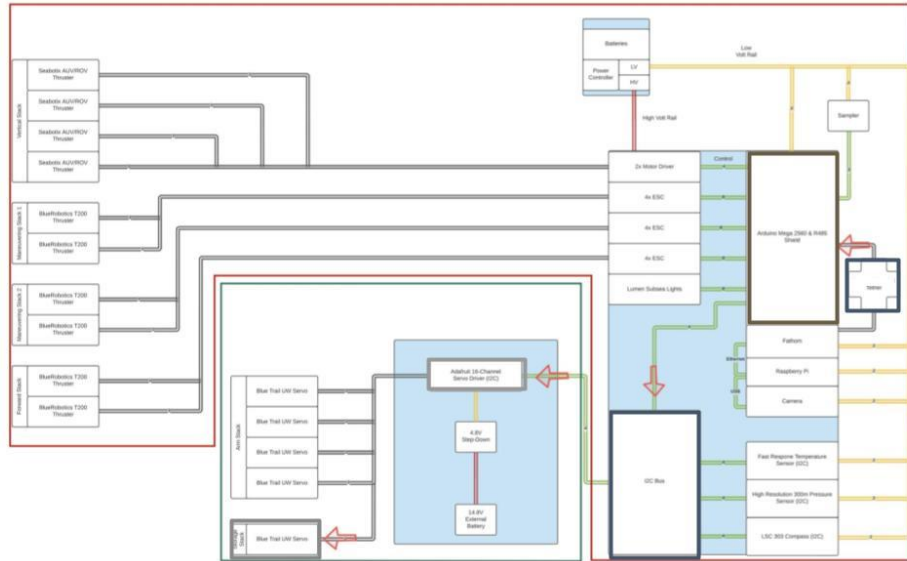


Electrical System





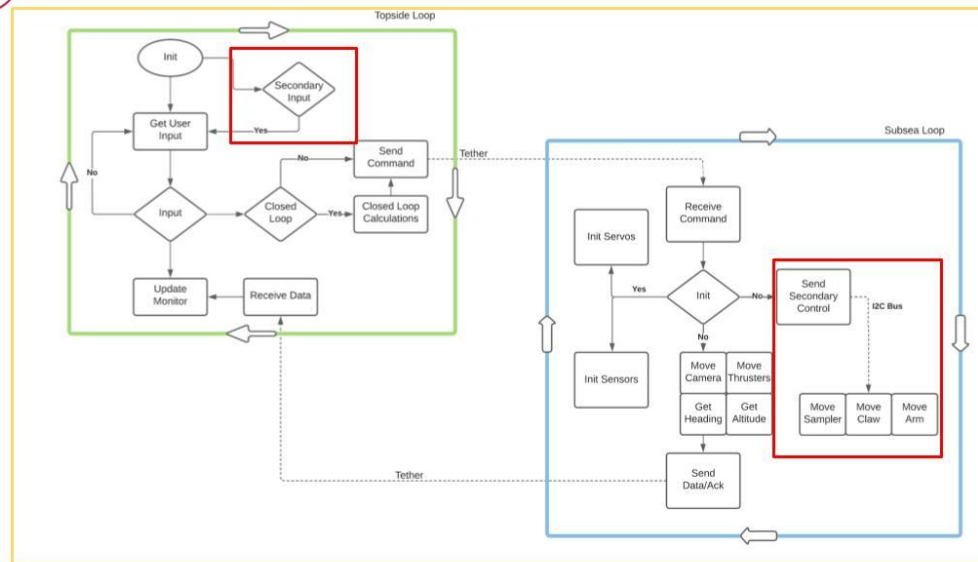
Wiring Diagram



28



Basic Software Diagram



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Software

- Added support for a second controller
- Having a dedicated controller allows for simple intuitive controls
- ROV movement and Arm control are separate
- We have unused buttons available for future controls
- Servo positions calculated topside to minimize computations on the arduino

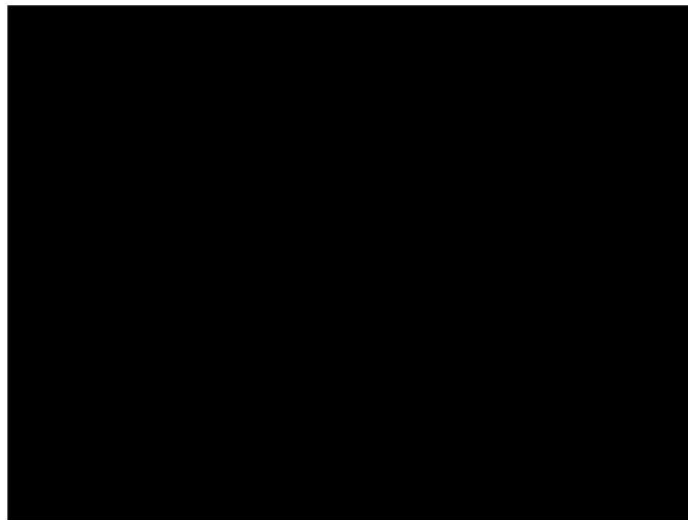




Testing



Video





Parameters & Endstate Outcomes

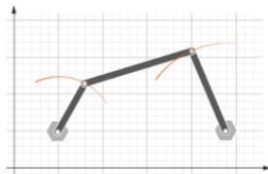
Collect 3 Samples in 45 Min	●
2in ³ Samples	●
1.6lb Samples	●
300 ft depth capability	●
Removable	●
Workspace	●
Neutrally buoyant	●

Key	
Unfulfilled	●
Untested	●
Fulfilled	●



Potential For Future Work

- Add bearing and change gears on storage system
- Simplify control system for ease of use
- 3D print battery holder
- Write a user manual
- Storage/transportation box
- Variable speed servo control
- Additional claw designs for specific tasks
- Custom servos for more force
- Rebuild for larger samples and more degrees of freedom



34



Organization and Team Management

- [Budget and BOM](#)
- Smartsheets
- Google Calendar



Servo Specs

Blue Trail Robotics Servos



- Up to 7 full turns
- Torque:
 - 34.0 kg-cm / 470 oz-in

Waterproof High-torque Servo
SER-120X, multi-turn, BLDC
motor

SKU: SER-1207

\$480.00

or 4 interest-free payments of
\$120 with [PayPal Learn More](#)

Digital, waterproof servo, submersible up
to 100 meters. Programmable rotation up
to 7 turns or continuous rotation.
Brushless motor and magnetic encoder.

SKU: SER-1207

Waterproof Servo SER-110X

SKU: SER-1107

\$380.00

or 4 interest-free payments of
\$95 with [PayPal Learn More](#)

Programmable, digital, waterproof servo,
submersible up to 100 meters.

- +/- 74 degree maximum rotation
- Torque:
 - 18.0 kg-cm / 250 oz-in @ 4.8 V
 - 29.0 kg-cm / 403 oz-in @ 7.4 V



Buoyancy Foam Specs



Tested Depth (Uncoated) - 300ft

Size - 12 x 6 x 1 in.

Net Buoyancy - 2.10 lb

Source: Blue Robotics Inc.



SANTA CLARA UNIVERSITY
SCHOOL OF ENGINEERING

Material Specs

PETG

Tensile $6.3 \cdot 10^7$ Pa

Yield $4.83 \cdot 10^7$ Pa

Density $1.27 \cdot 10^3$ Kg/m³

Acrylic

Tensile $7.25 \cdot 10^7$ Pa

Yield $7.45 \cdot 10^7$ Pa

Density $1.18 \cdot 10^3$ Kg/m³

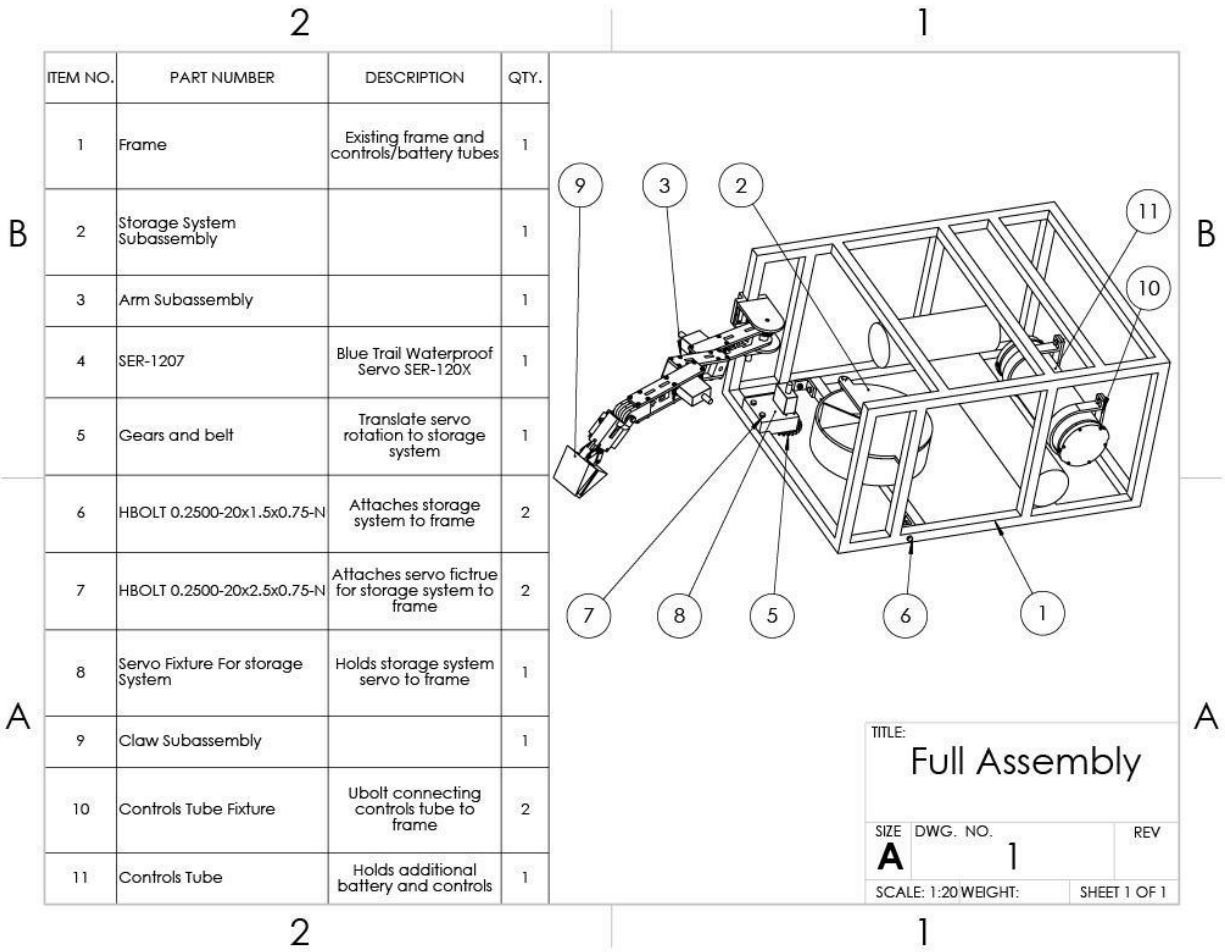
6061 Aluminum

Tensile $2.9 \cdot 10^8$ Pa

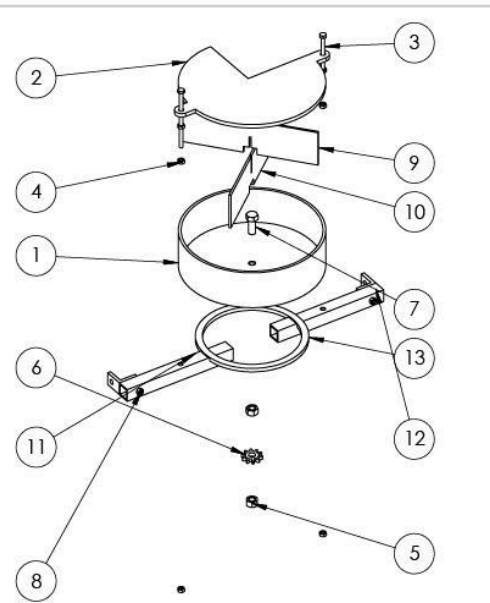
Yield $2.4 \cdot 10^8$ Pa

Density $2.7 \cdot 10^3$ Kg/m³

Appendix G: Engineering Drawings

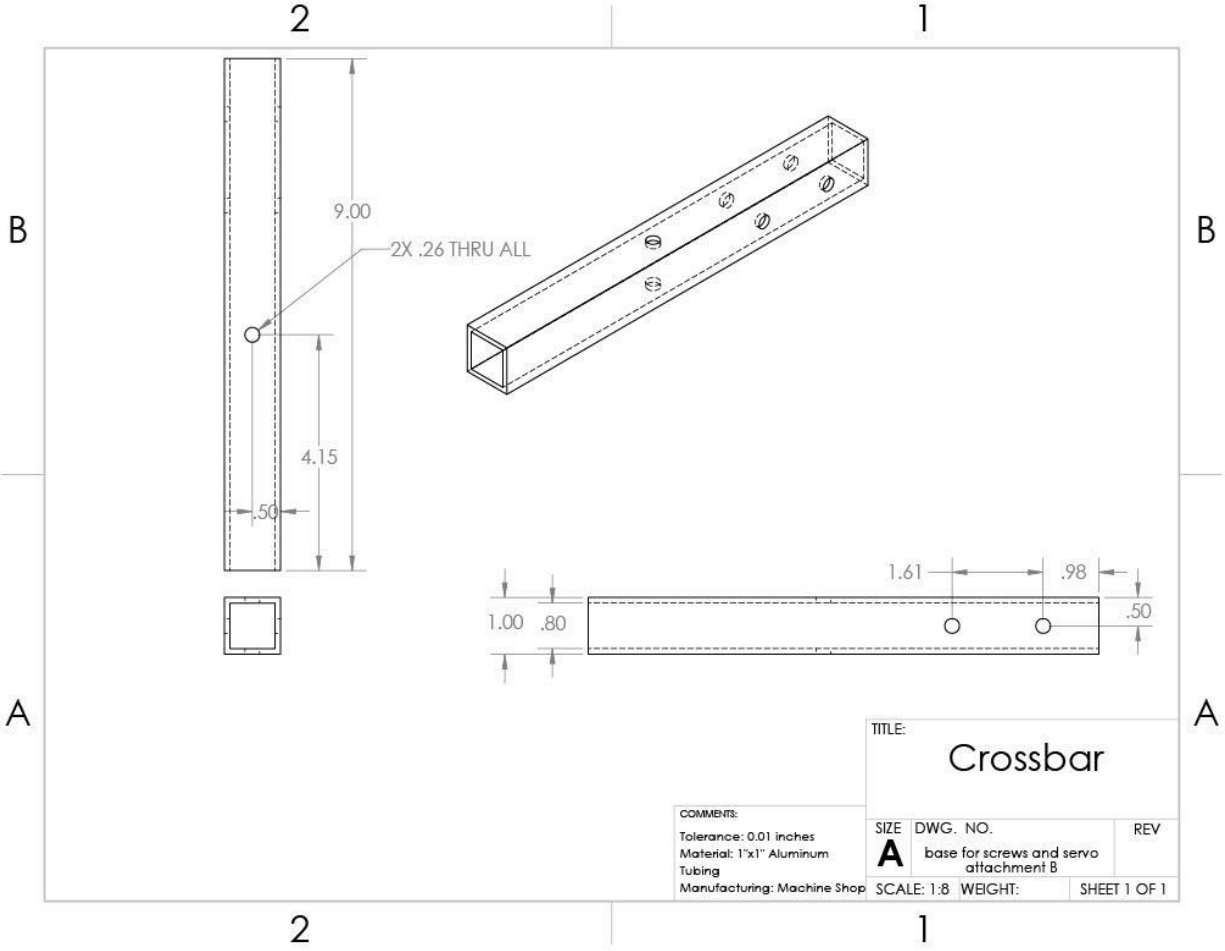


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	MAIN STORAGE TIN	ROTATING MAIN STORAGE CONTAINER FOR SAMPLES	1
2	LID	KEEPS SAMPLES IN PLACE- OPENING OVER ONE QUARTER STAYS STATIC FOR SAMPLE DEPOSIT	1
3	HBOLT 0.2500-20x4.75x0.75-N		2
4	HNUT 0.2500-20-D-N		8
5	HNUT 0.5000-13-D-N		2
6	Inch - Spur gear 8DP 10T 14.5PA 0.25FW — S10N3.0H2.0L0.5N	Translates Motion from servo and 25 tooth gear to rotate main storage tin	1
7	HBOLT 0.5000-13x1.25x1.25-N		1
8	HBOLT 0.2500-20x1.5x0.75-N		2
9	DIVIDER_A	LINKS WITH DIVIDER_B TO SEPERATE UP TO 3 SAMPLES	1
10	DIVIDER_B	LINKS WITH DIVIDER_A TO SEPERATE UP TO 3 SAMPLES	1
11	BASE FOR SCREWS AND SERVO ATTACHMENT B	INVERSE SUPPORT PARTS THAT LID BEARING AND CAKE TIN SIT UPOMN	1
12	CORNER BRACKET	HOLDS CROSSBAR TO MAIN FRAME	2
13	DELRINBUSHING	REDUCES FRICTION ON CROSSBAR AS MAIN TIN ROTATES	1

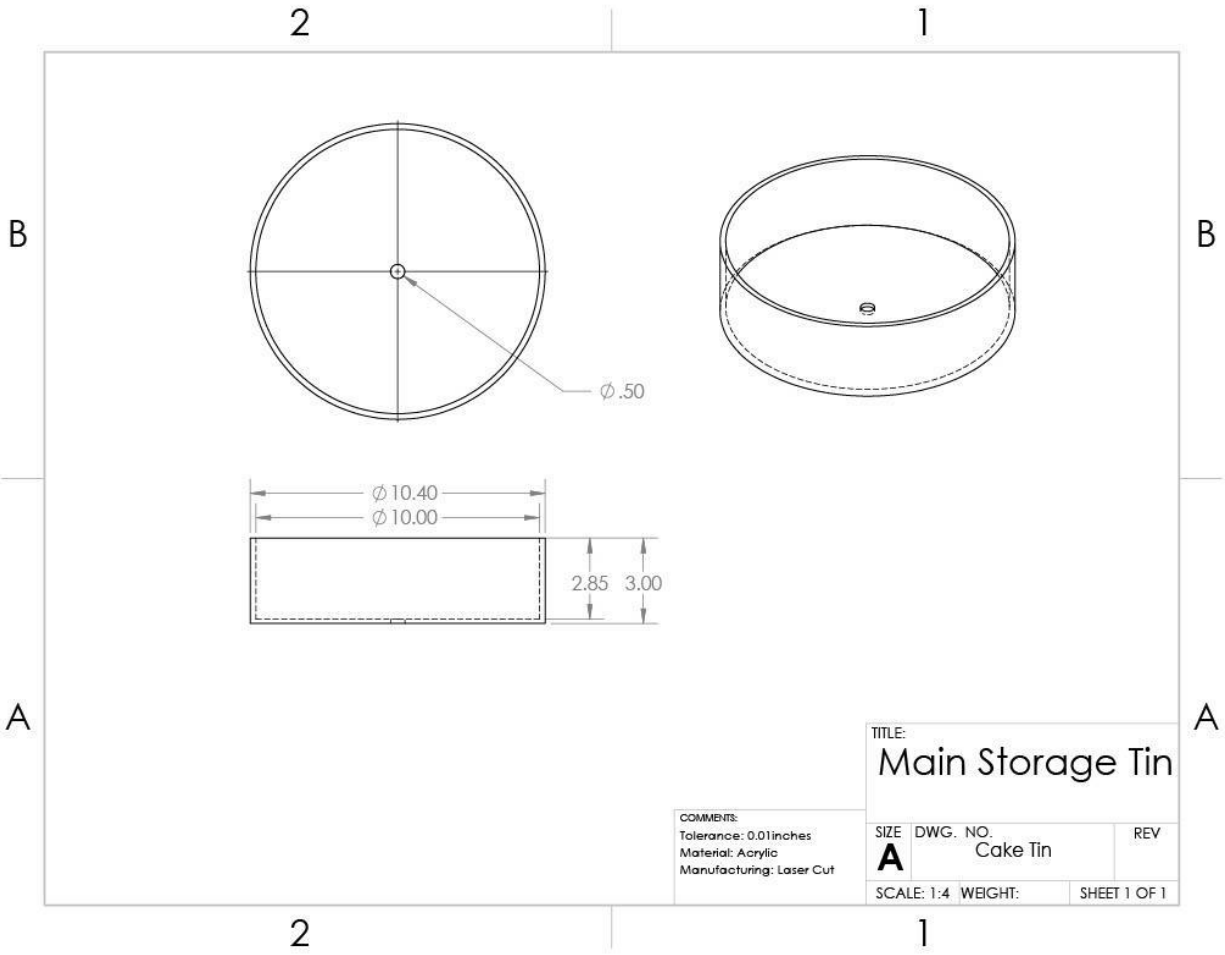


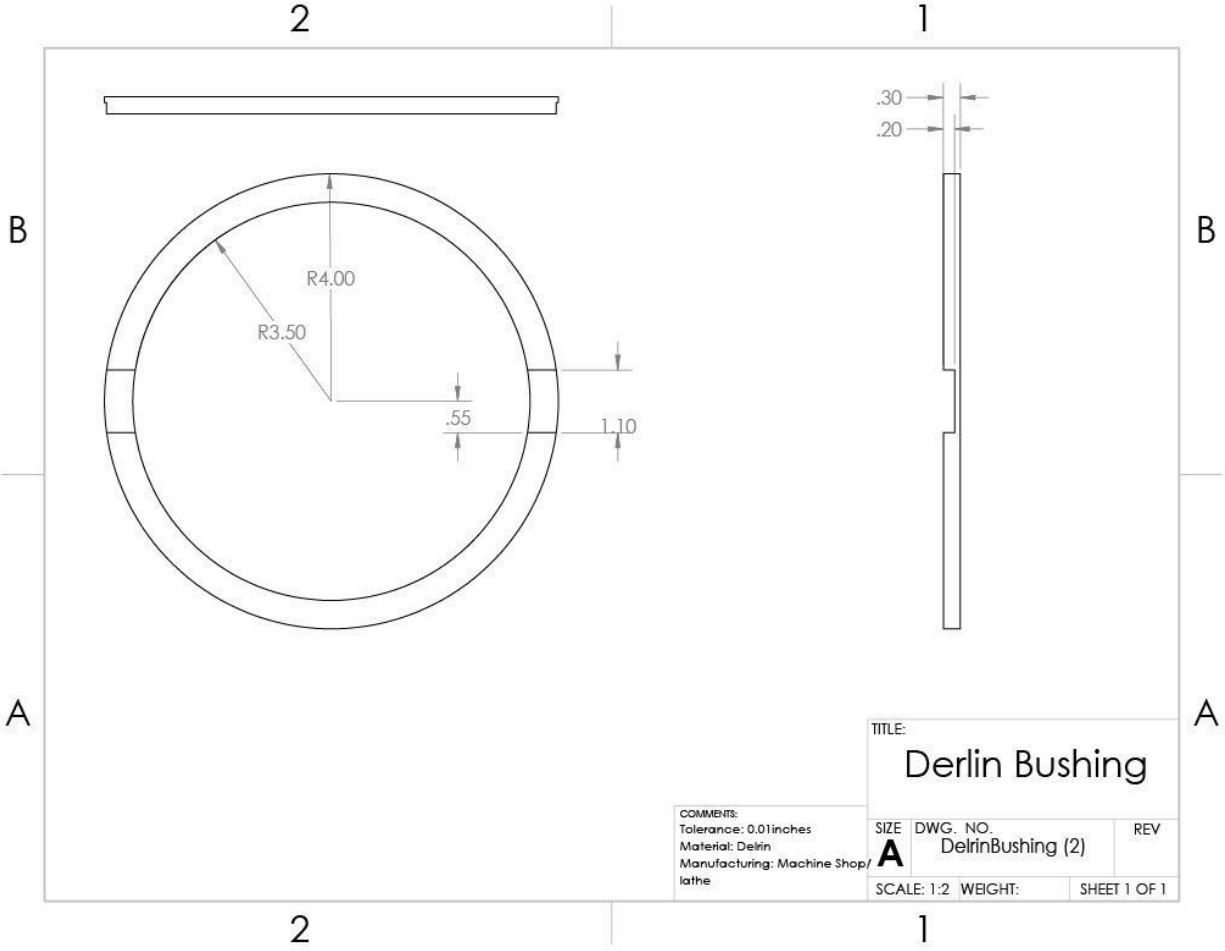
TITLE:
**Storage System
 Sub Assembly**

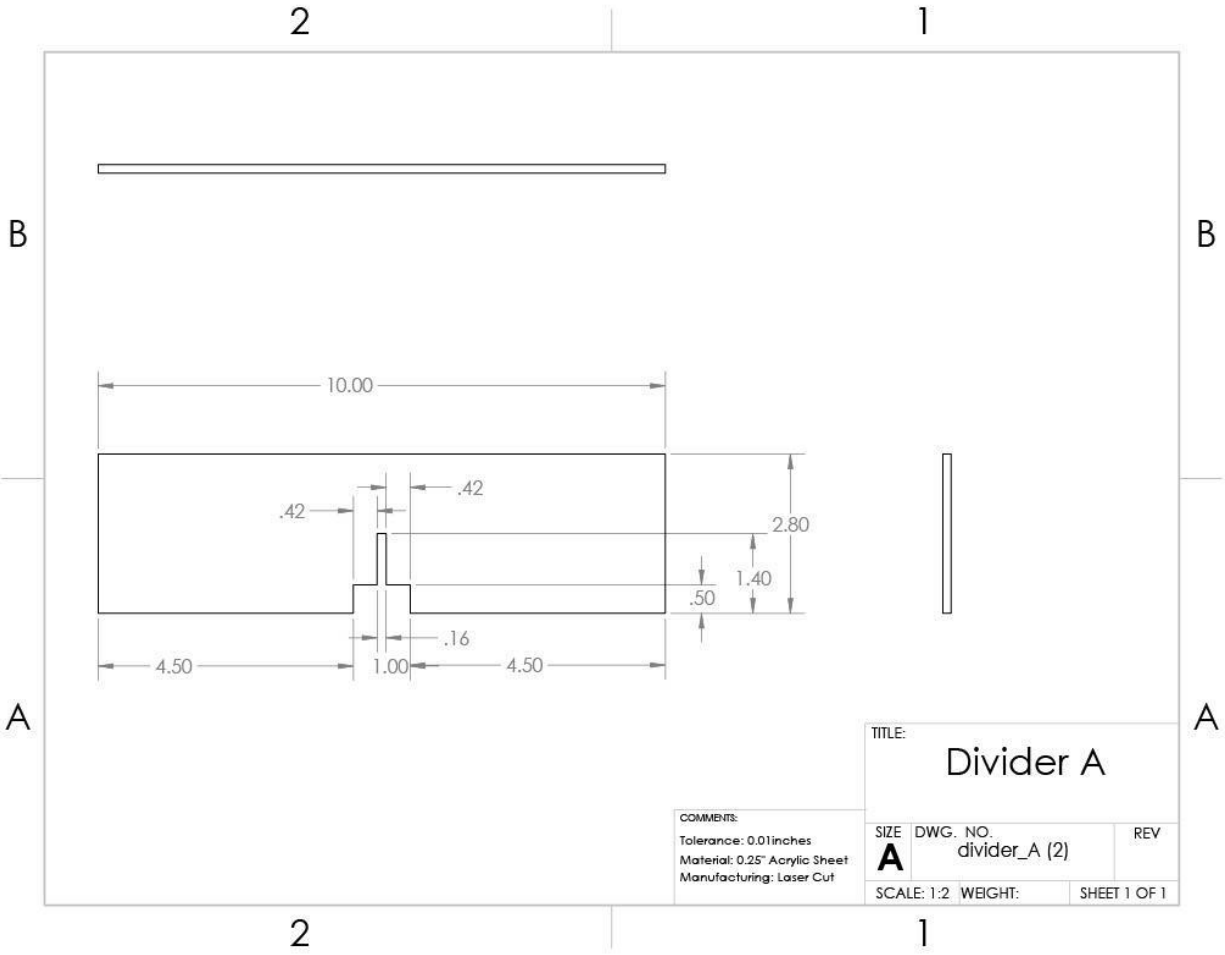
SIZE A	DWG. NO. Assem3	REV
SCALE: 1:16 WEIGHT:		SHEET 1 OF 1

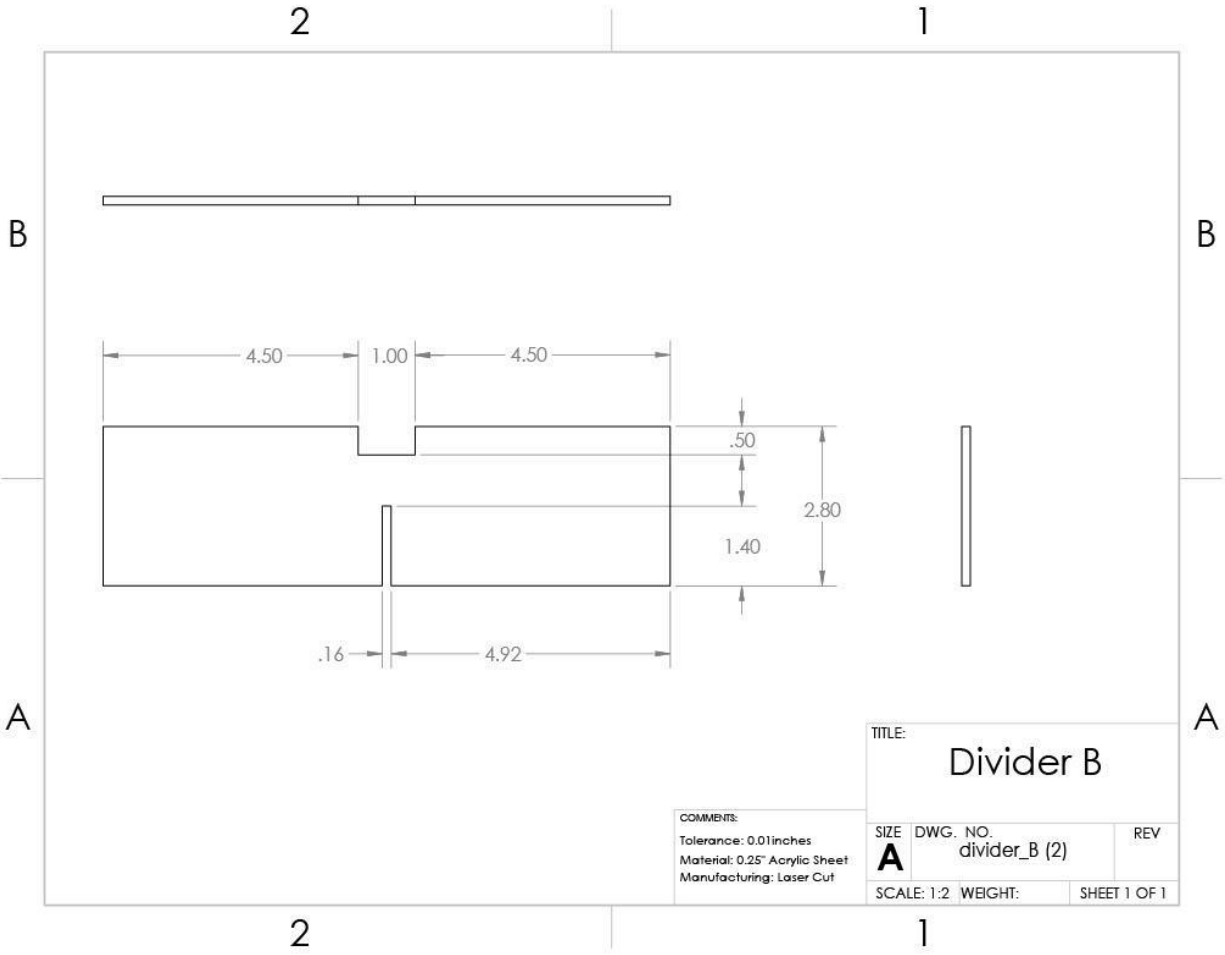


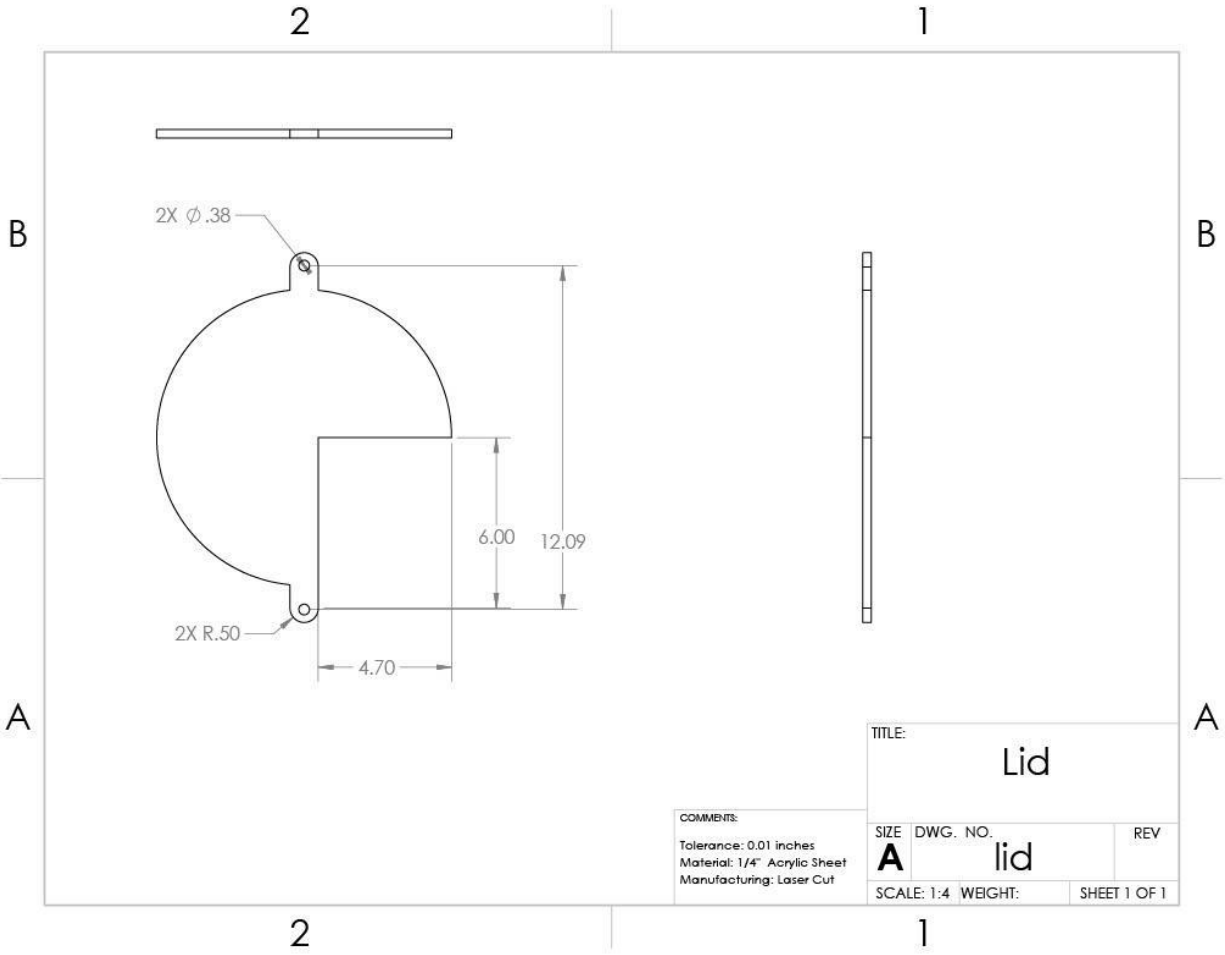
TITLE:		
Crossbar		
COMMENTS:	SIZE	DWG. NO.
Tolerance: 0.01 inches	A	base for screws and servo attachment B
Material: 1"x1" Aluminum Tubing	SCALE: 1:8	WEIGHT:
Manufacturing: Machine Shop		SHEET 1 OF 1

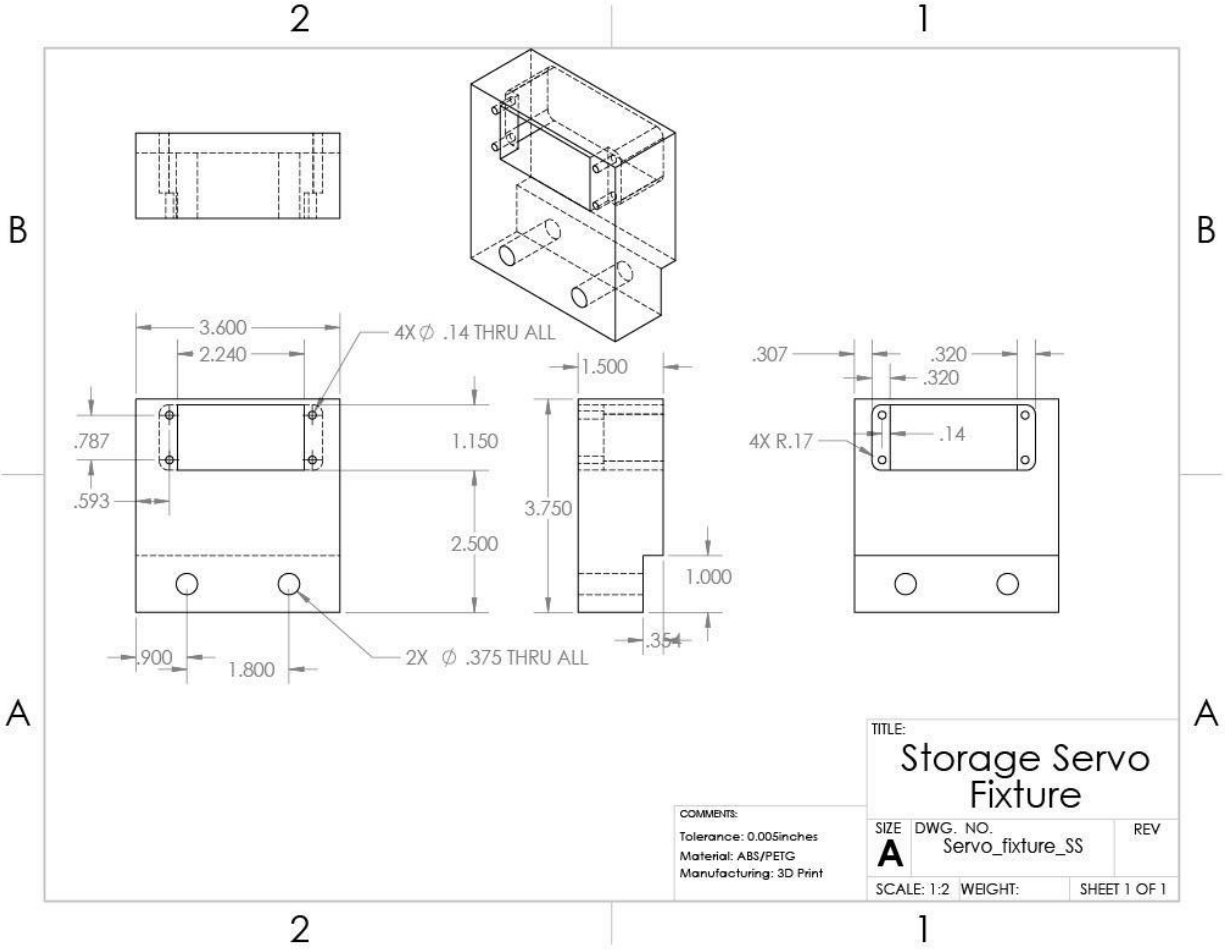






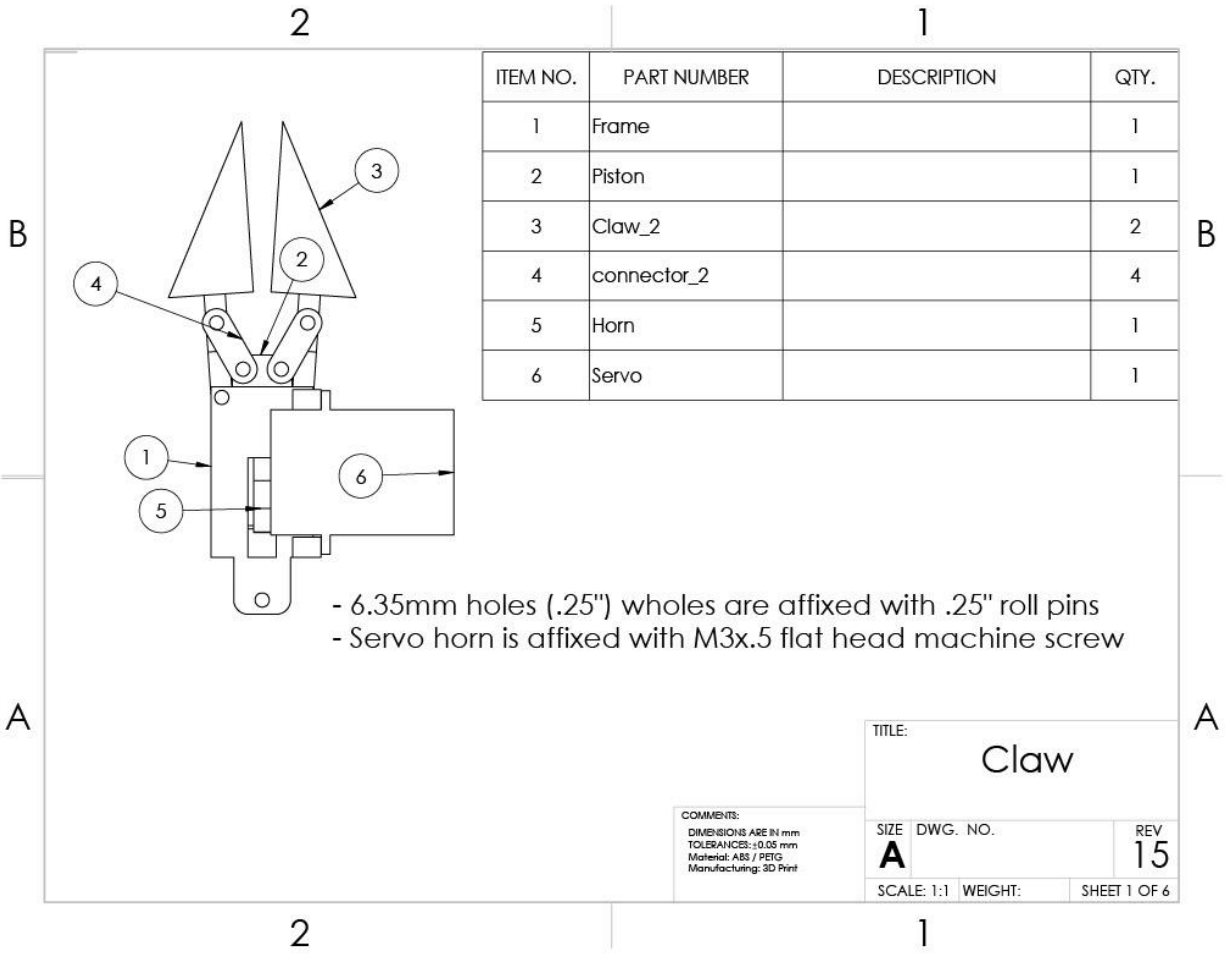






TITLE:		
Storage Servo Fixture		
SIZE	DWG. NO.	REV
A	Servo_fixture_SS	
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

COMMENTS:
Tolerance: 0.005inches
Material: ABS/PETG
Manufacturing: 3D Print

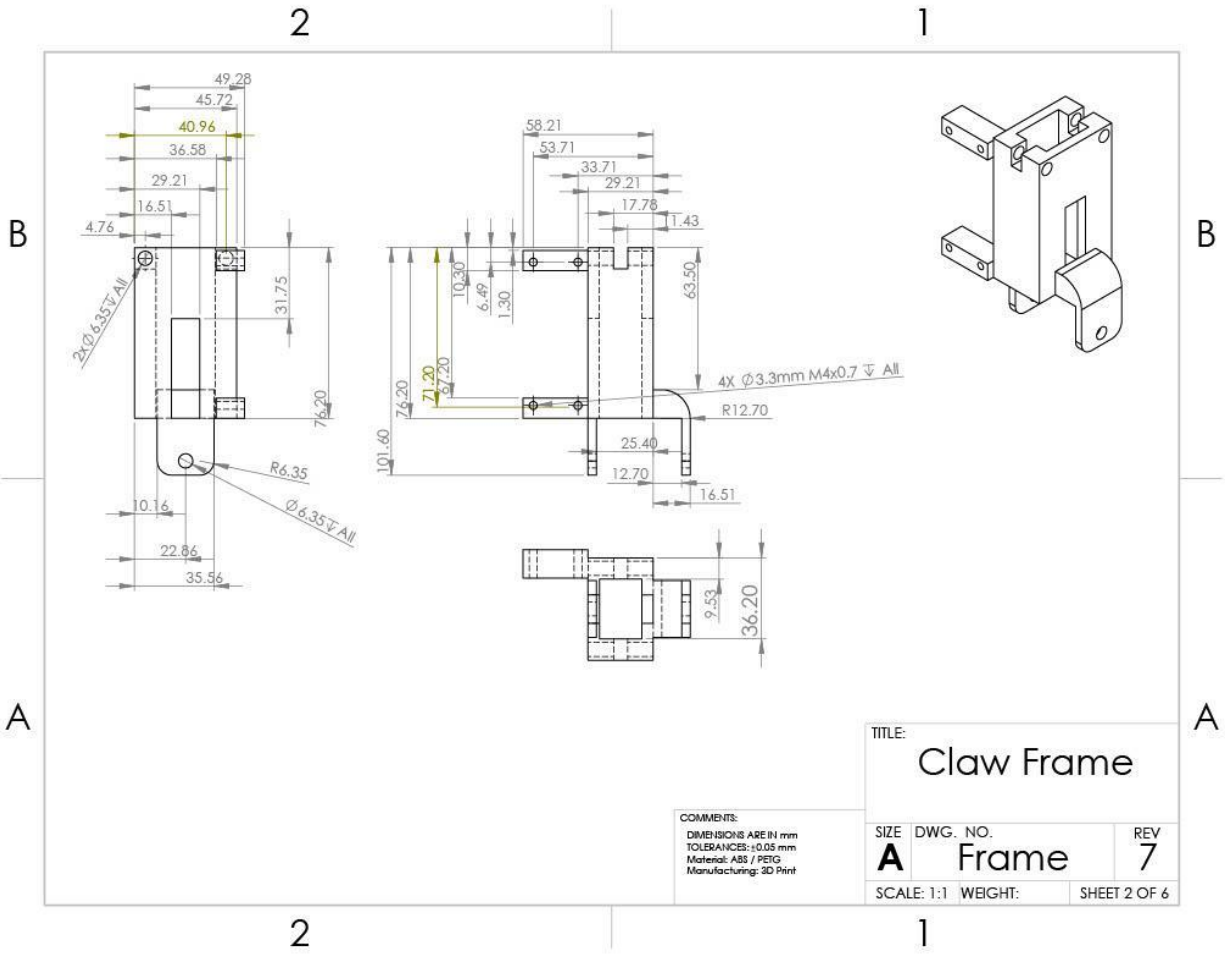


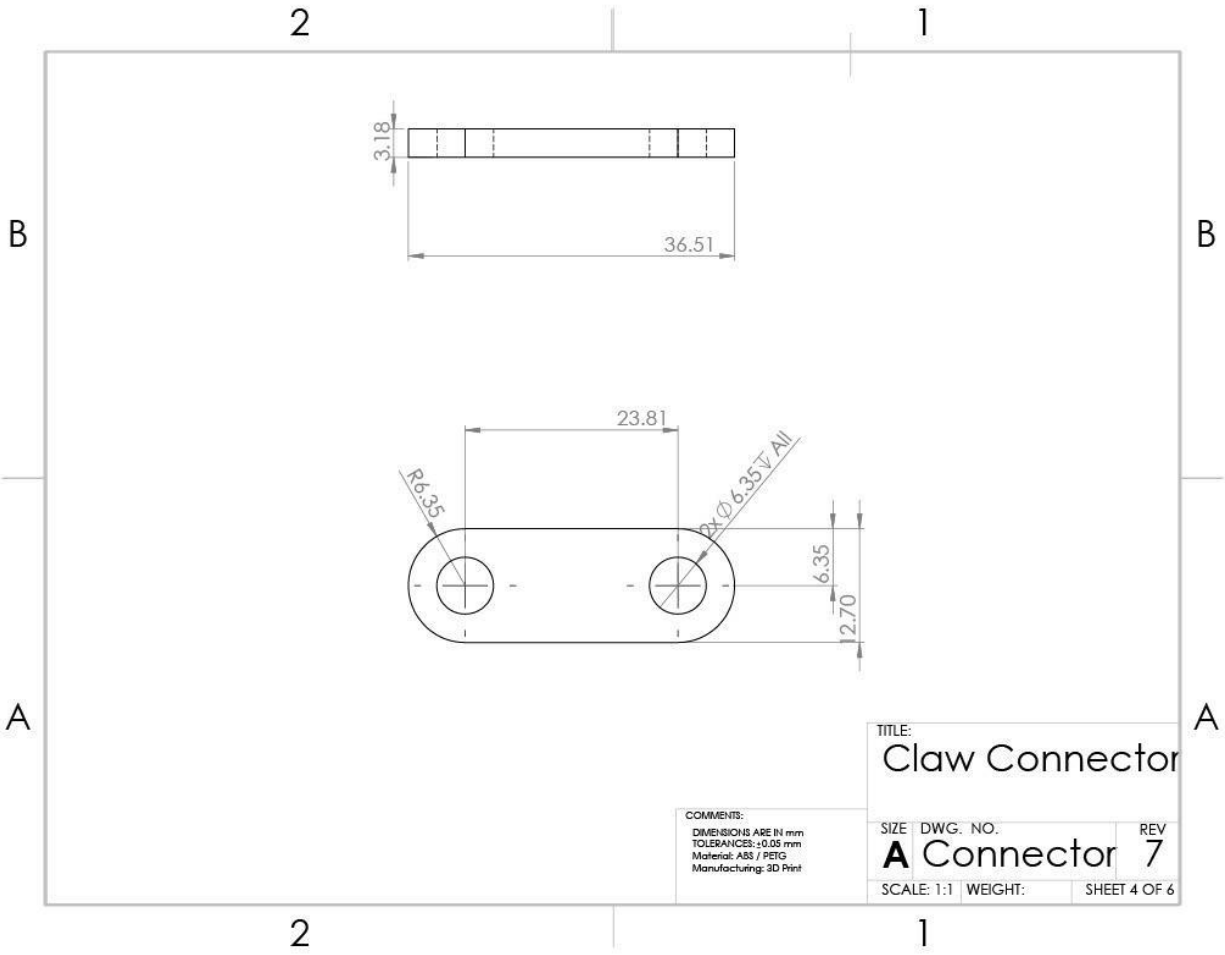
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Frame		1
2	Piston		1
3	Claw_2		2
4	connector_2		4
5	Horn		1
6	Servo		1

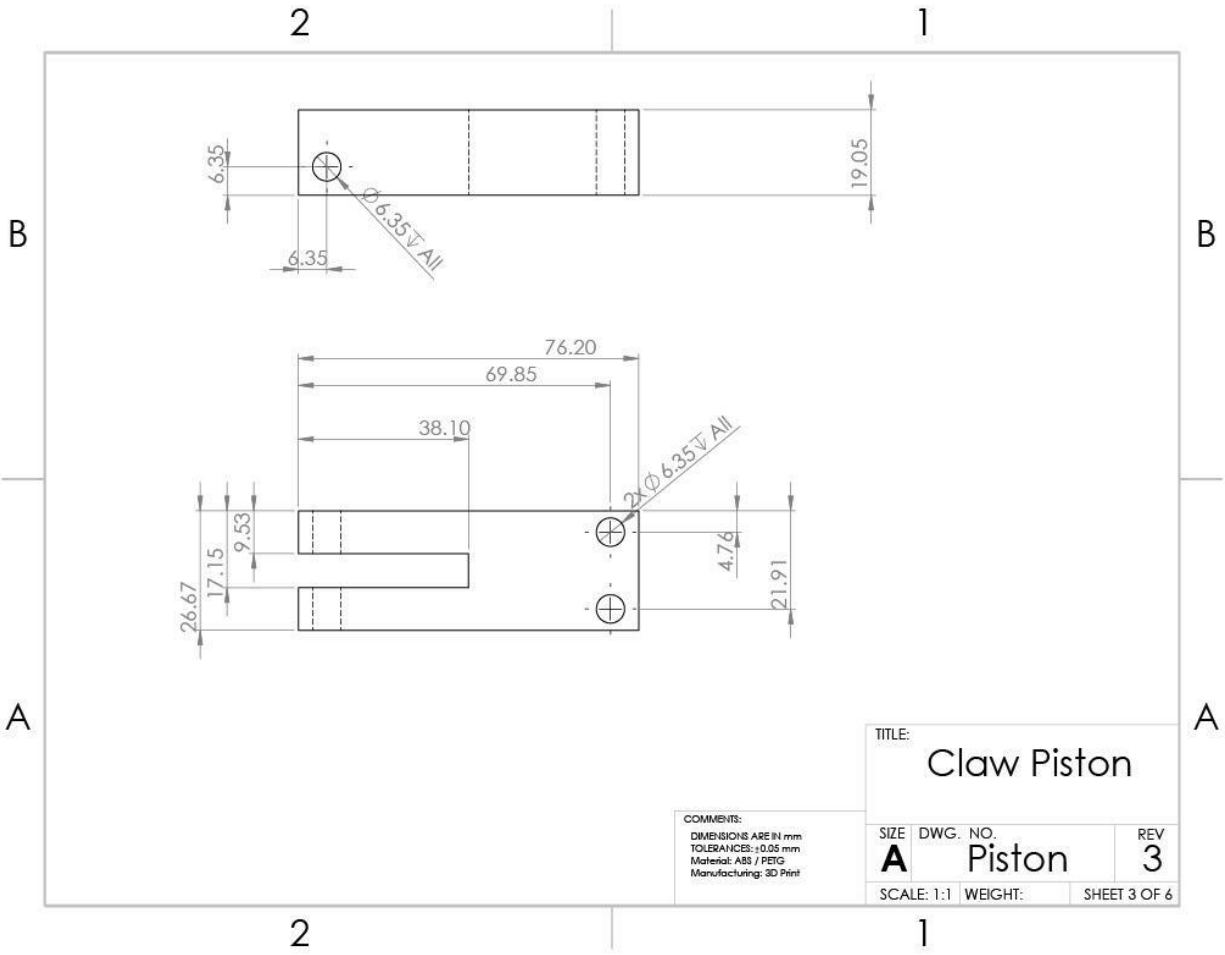
- 6.35mm (.25") holes are affixed with .25" roll pins
 - Servo horn is affixed with M3x.5 flat head machine screw

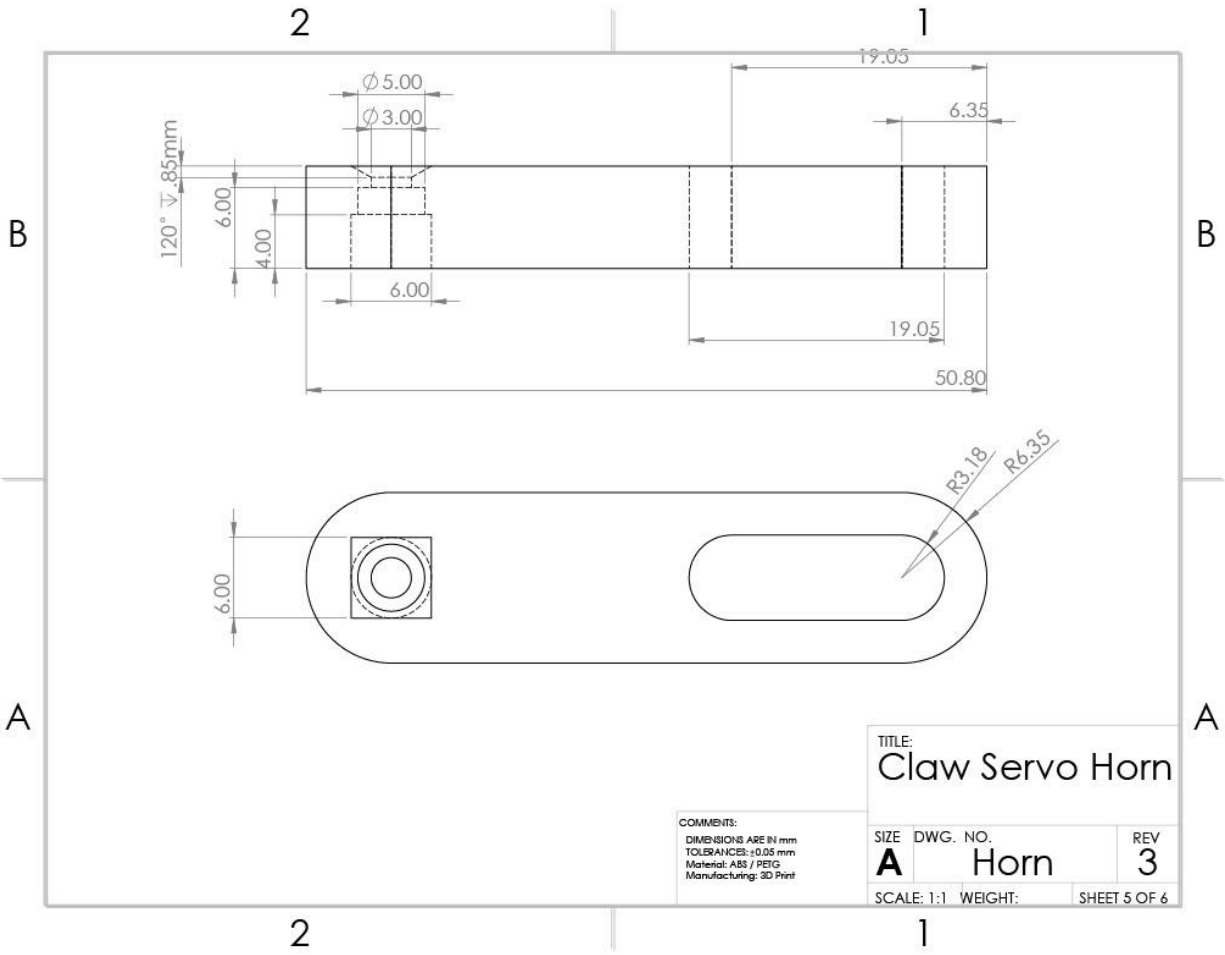
TITLE:		
Claw		
SIZE	DWG. NO.	REV
A		15
SCALE: 1:1	WEIGHT:	SHEET 1 OF 6

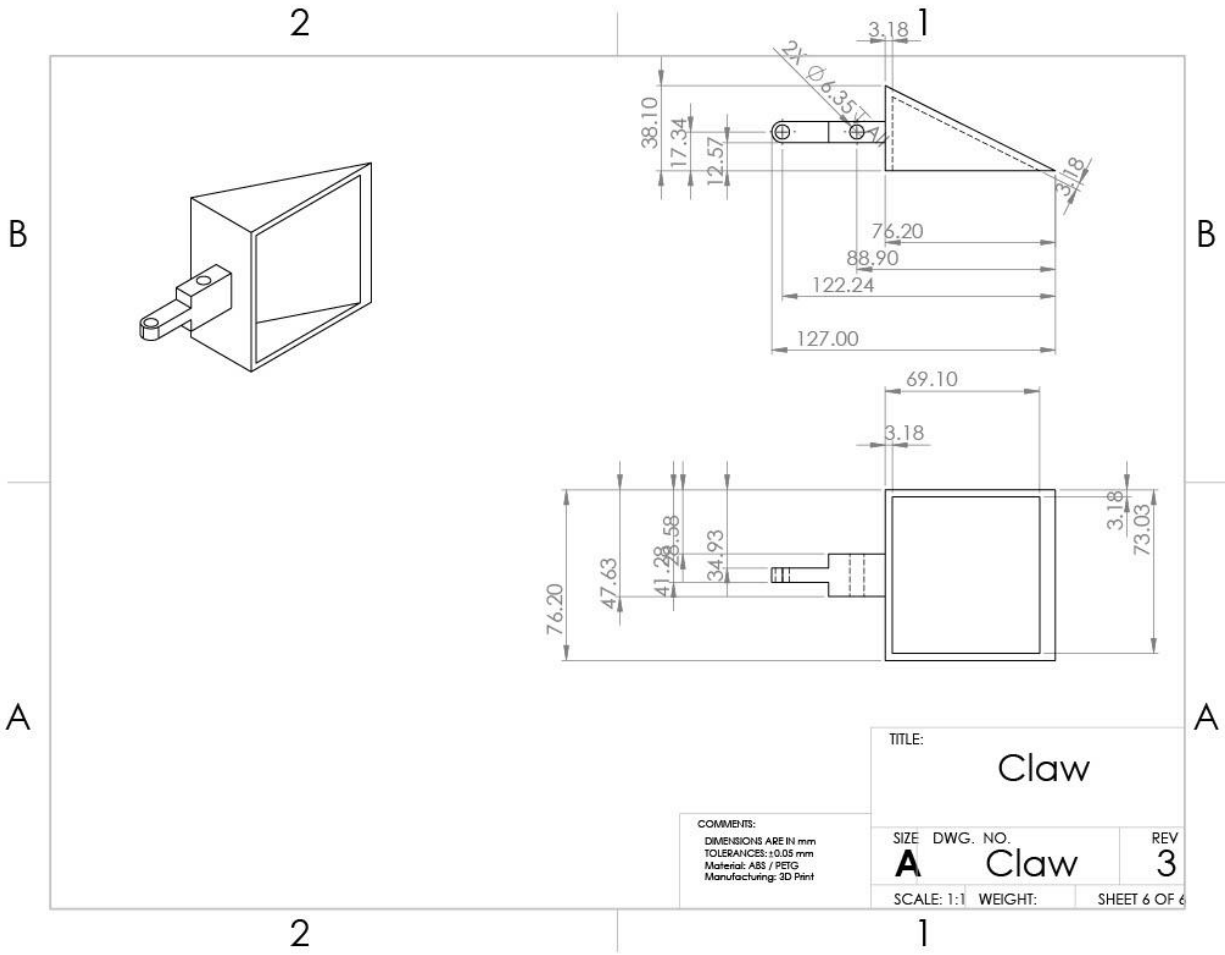
COMMENTS:
 DIMENSIONS ARE IN mm
 TOLERANCES: ±0.05 mm
 Material: ABS / PETG
 Manufacturing: 3D Print

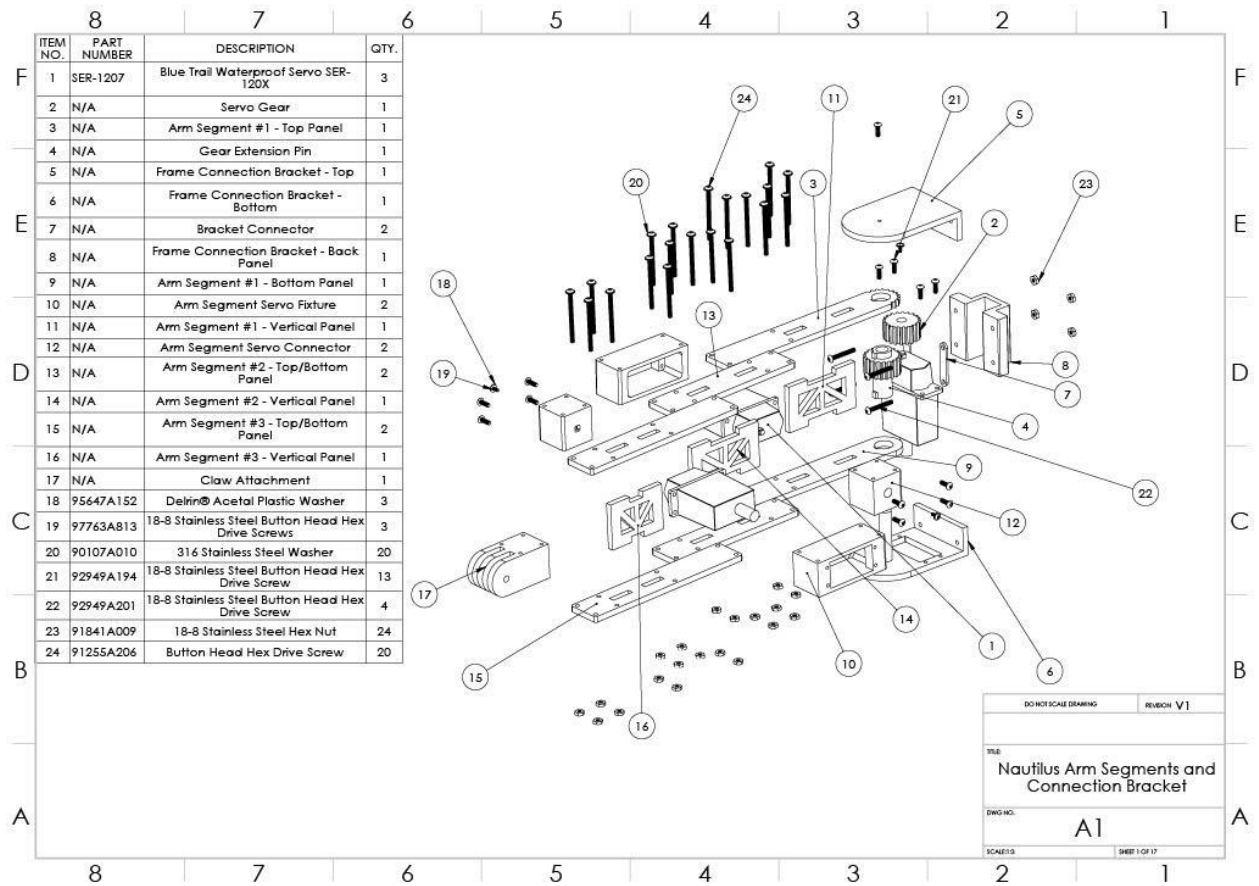


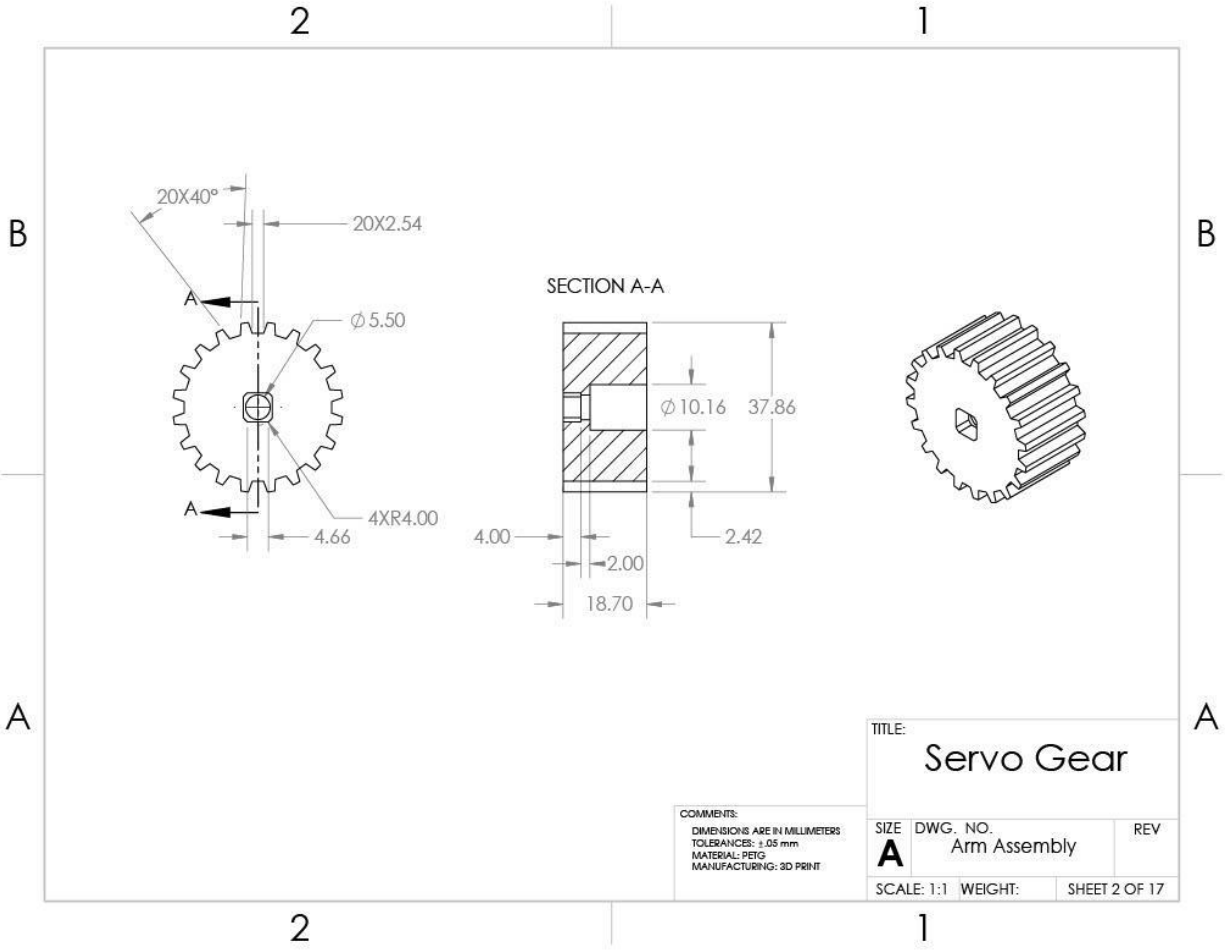


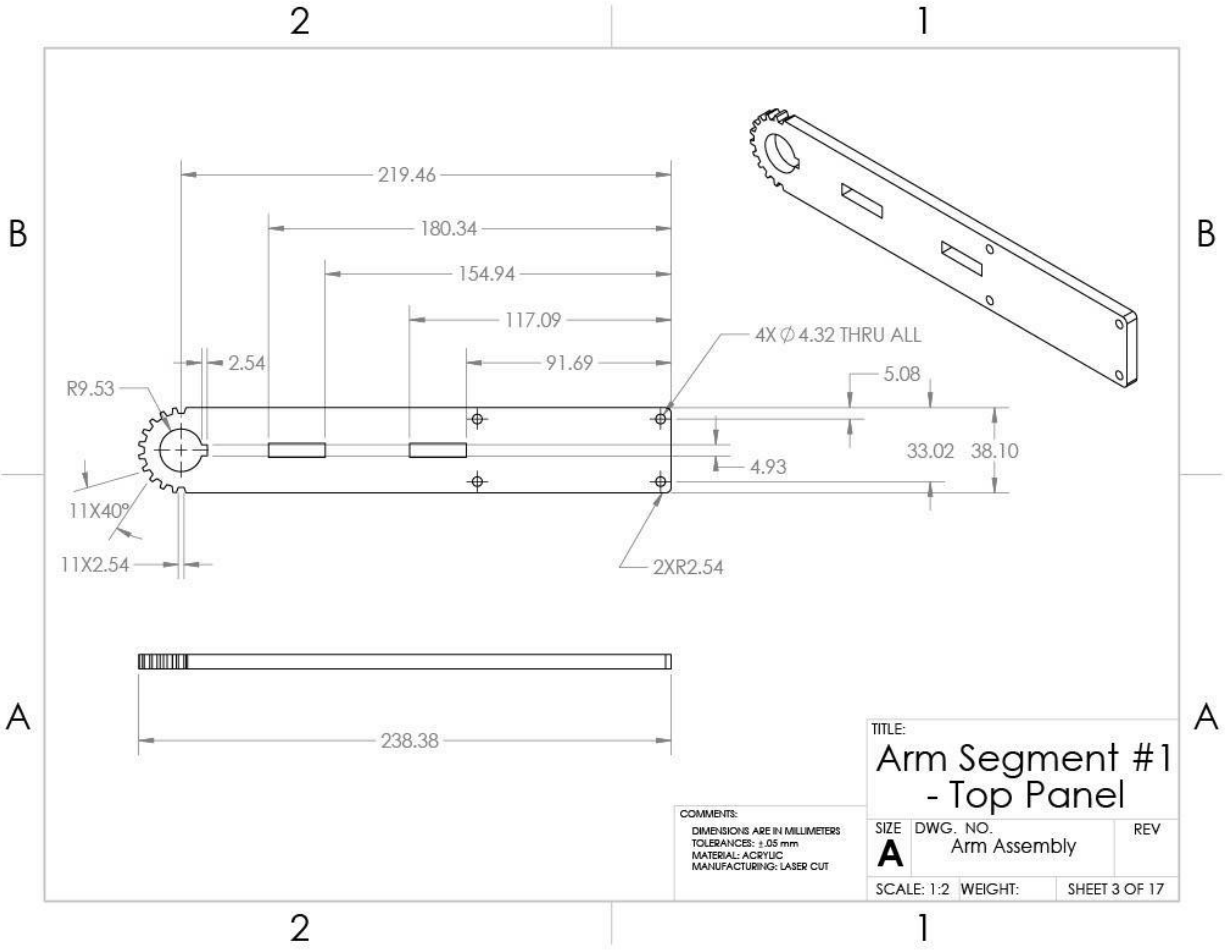






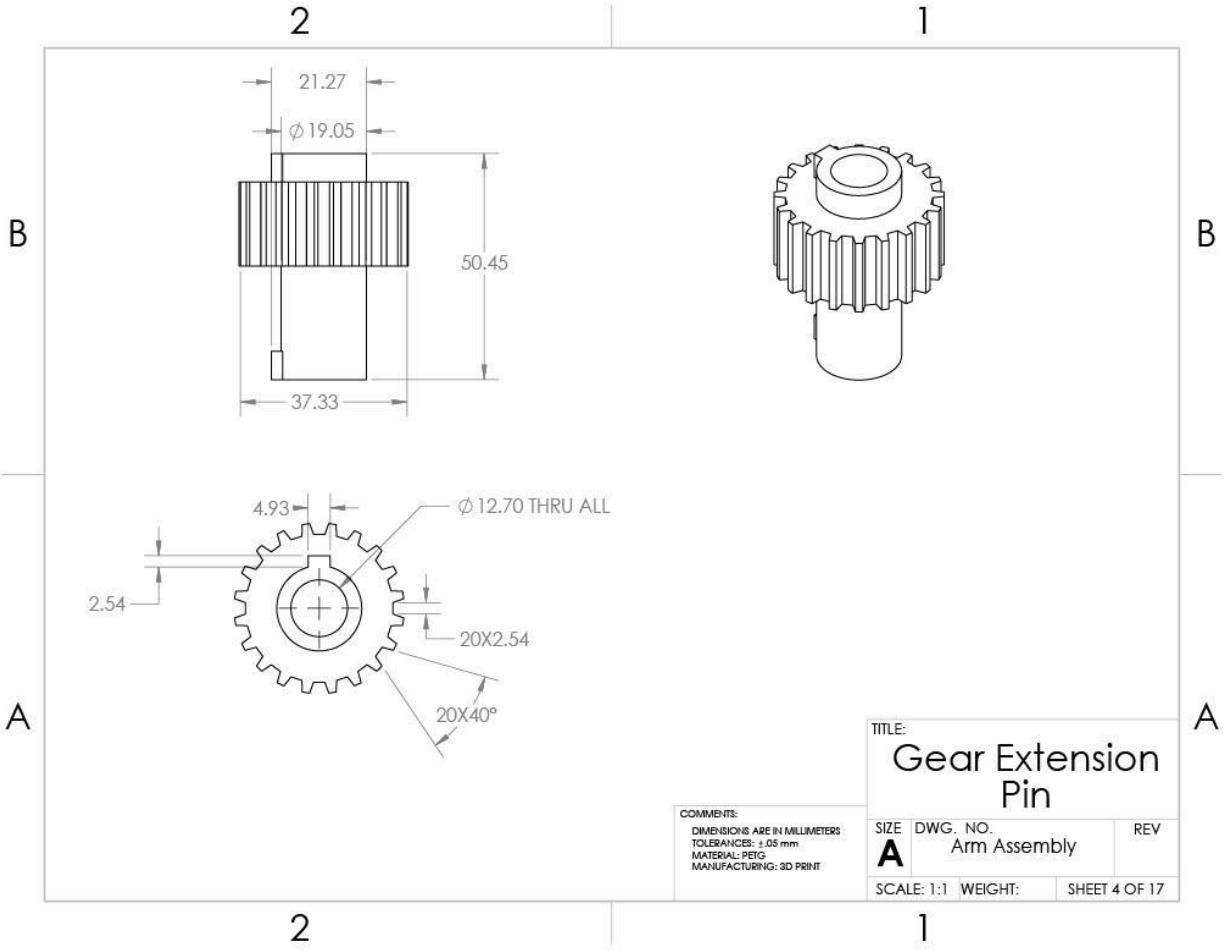


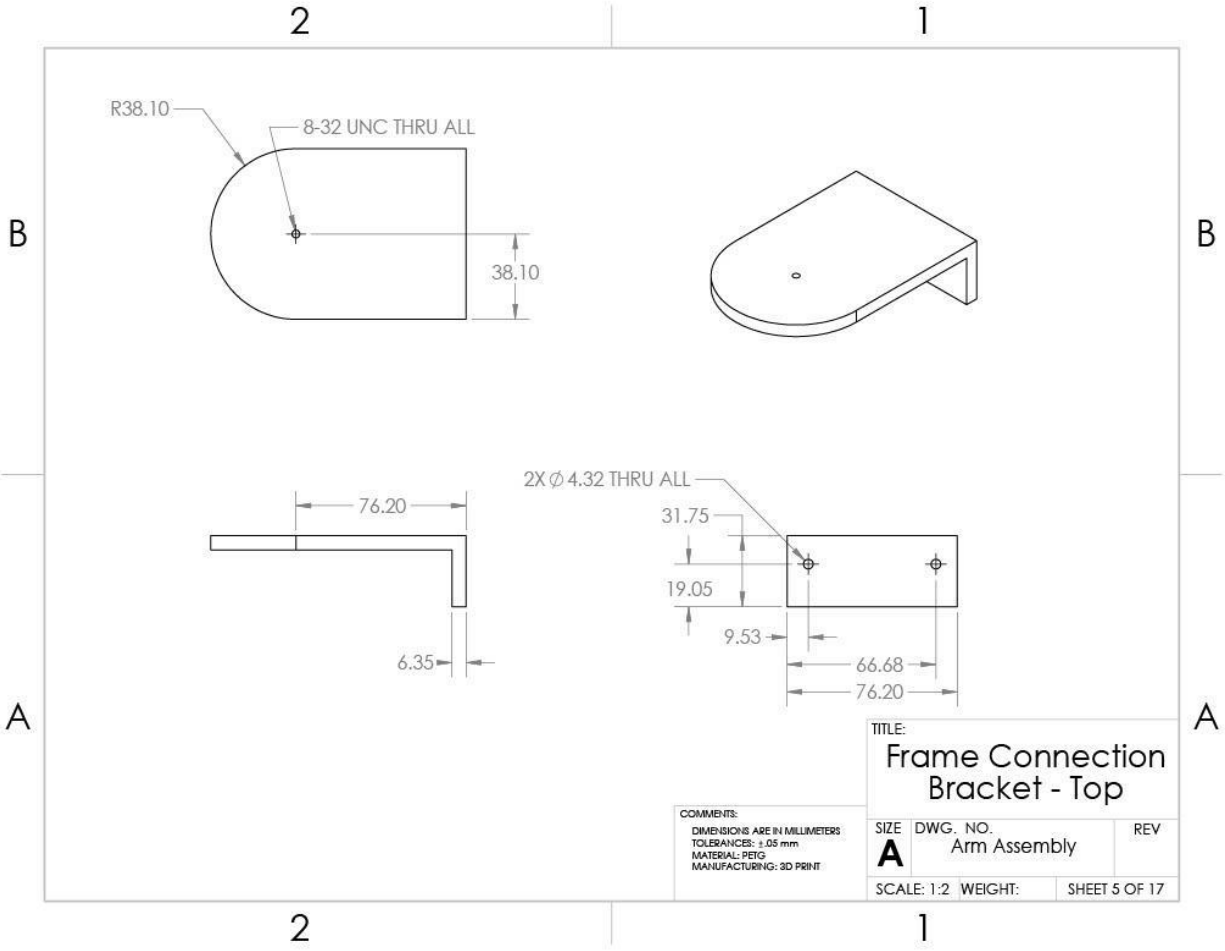




TITLE:		
Arm Segment #1 - Top Panel		
SIZE	DWG. NO.	REV
A	Arm Assembly	
SCALE: 1:2	WEIGHT:	SHEET 3 OF 17

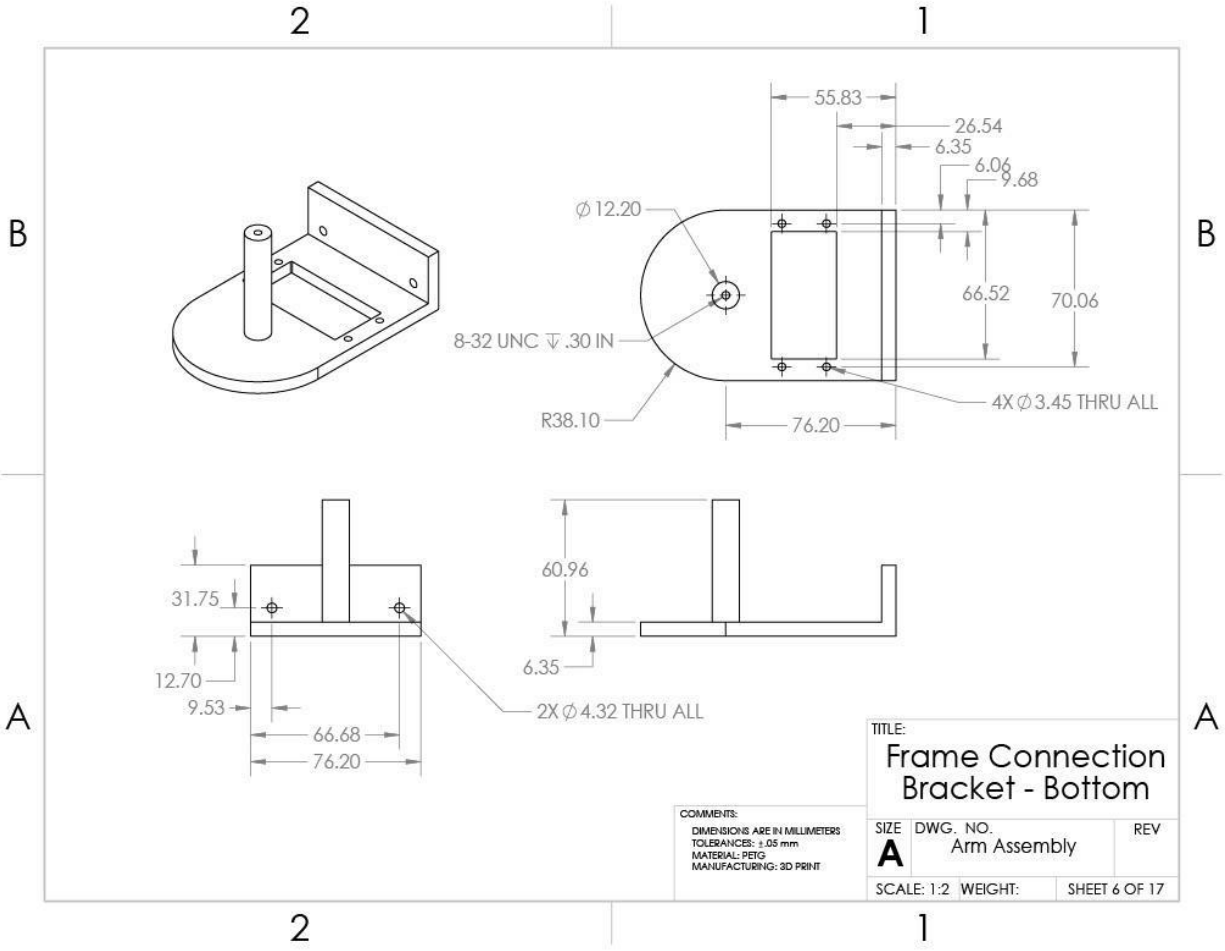
COMMENTS:
 DIMENSIONS ARE IN MILLIMETERS
 TOLERANCES: ± 0.05 mm
 MATERIAL: ACRYLIC
 MANUFACTURING: LASER CUT

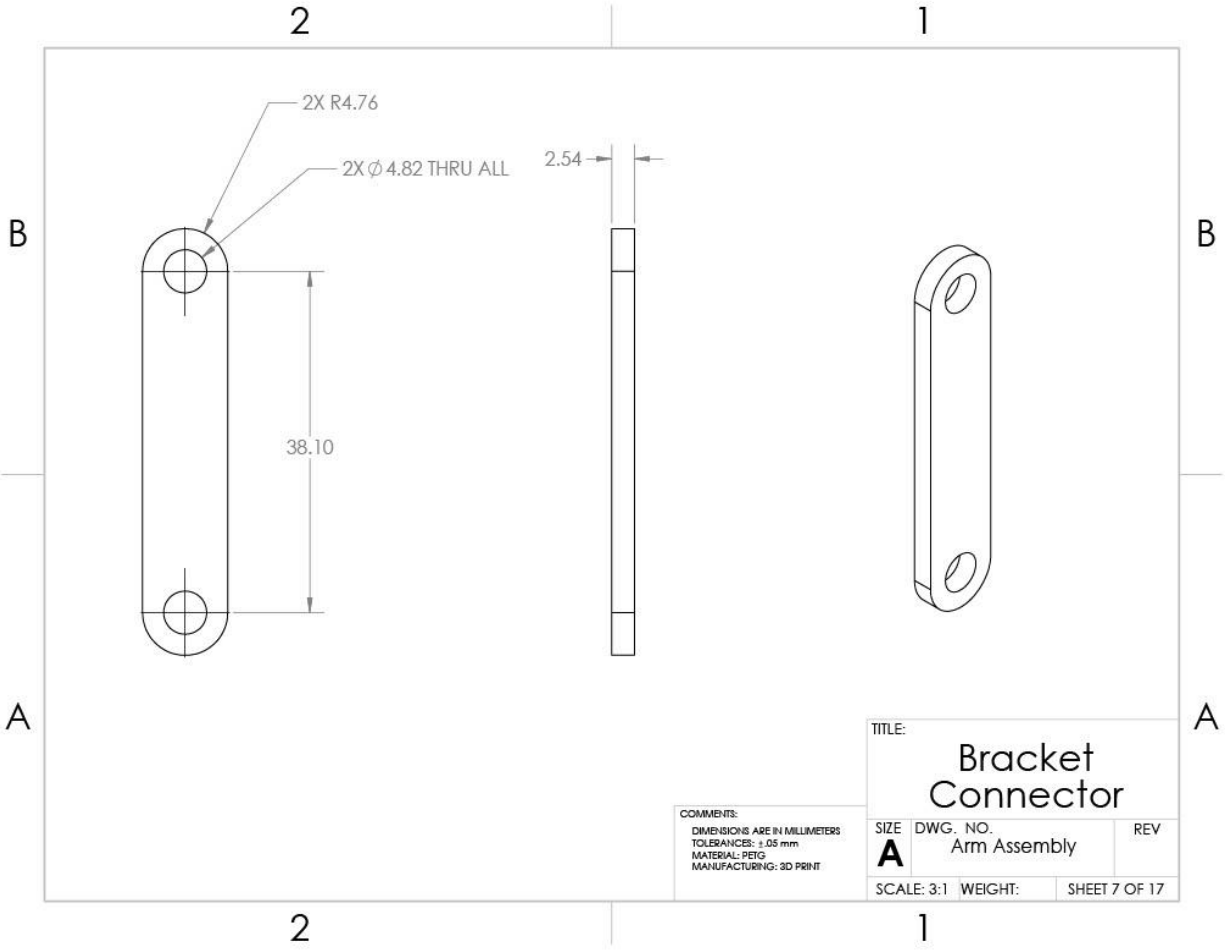


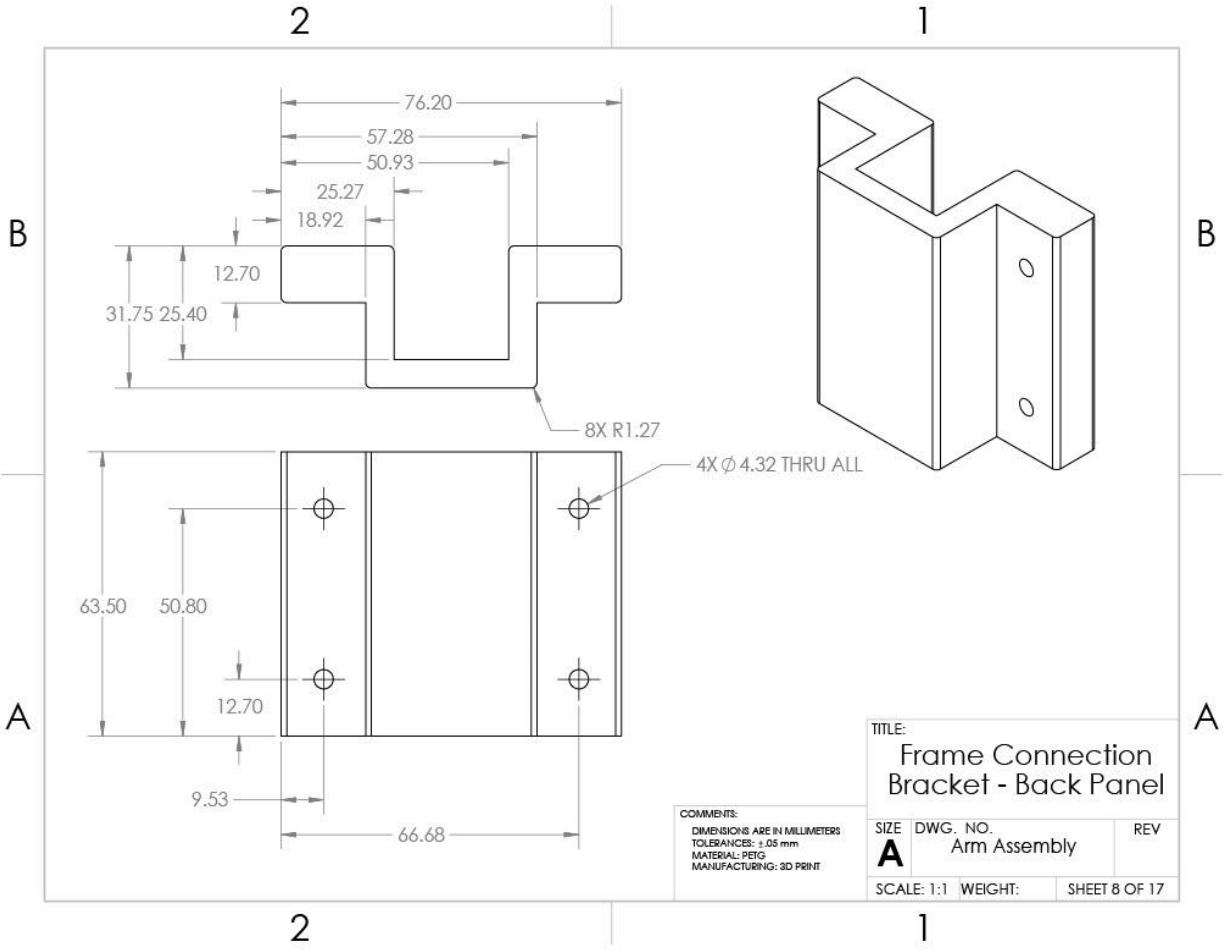


TITLE:		
Frame Connection Bracket - Top		
SIZE	DWG. NO.	REV
A	Arm Assembly	
SCALE: 1:2	WEIGHT:	SHEET 5 OF 17

COMMENTS:
 DIMENSIONS ARE IN MILLIMETERS
 TOLERANCES: ± 0.05 mm
 MATERIAL: PETG
 MANUFACTURING: 3D PRINT

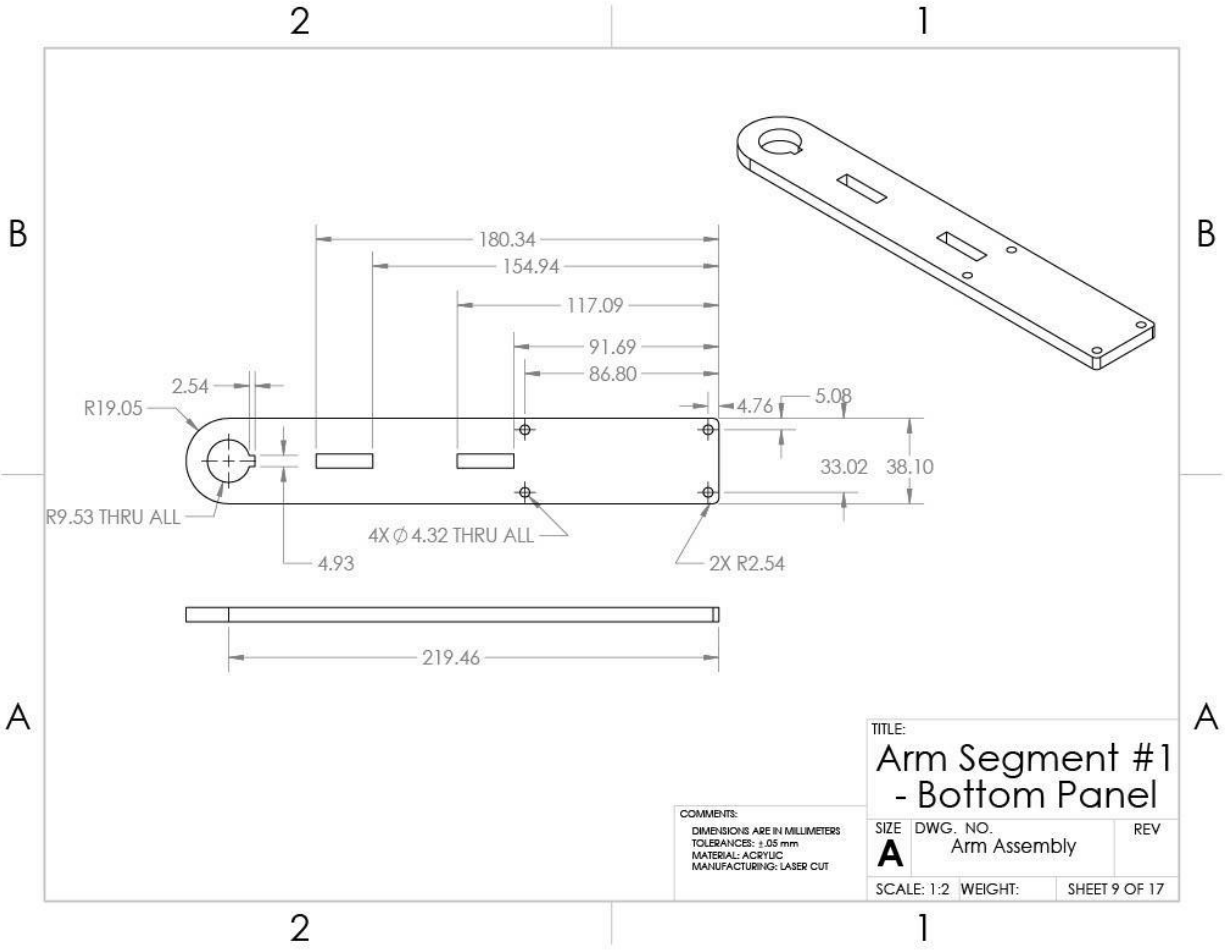






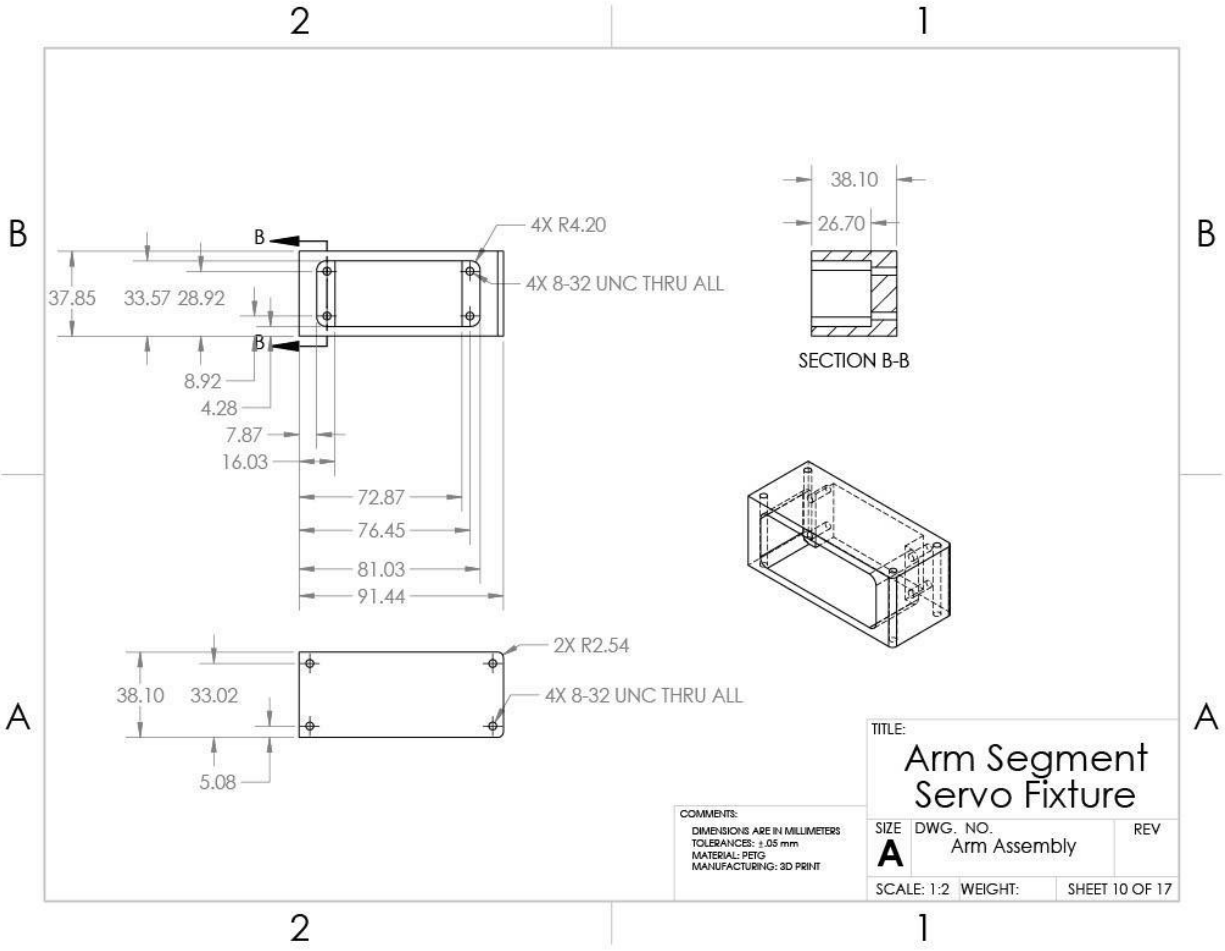
TITLE:		
Frame Connection Bracket - Back Panel		
SIZE	DWG. NO.	REV
A	Arm Assembly	
SCALE: 1:1	WEIGHT:	SHEET 8 OF 17

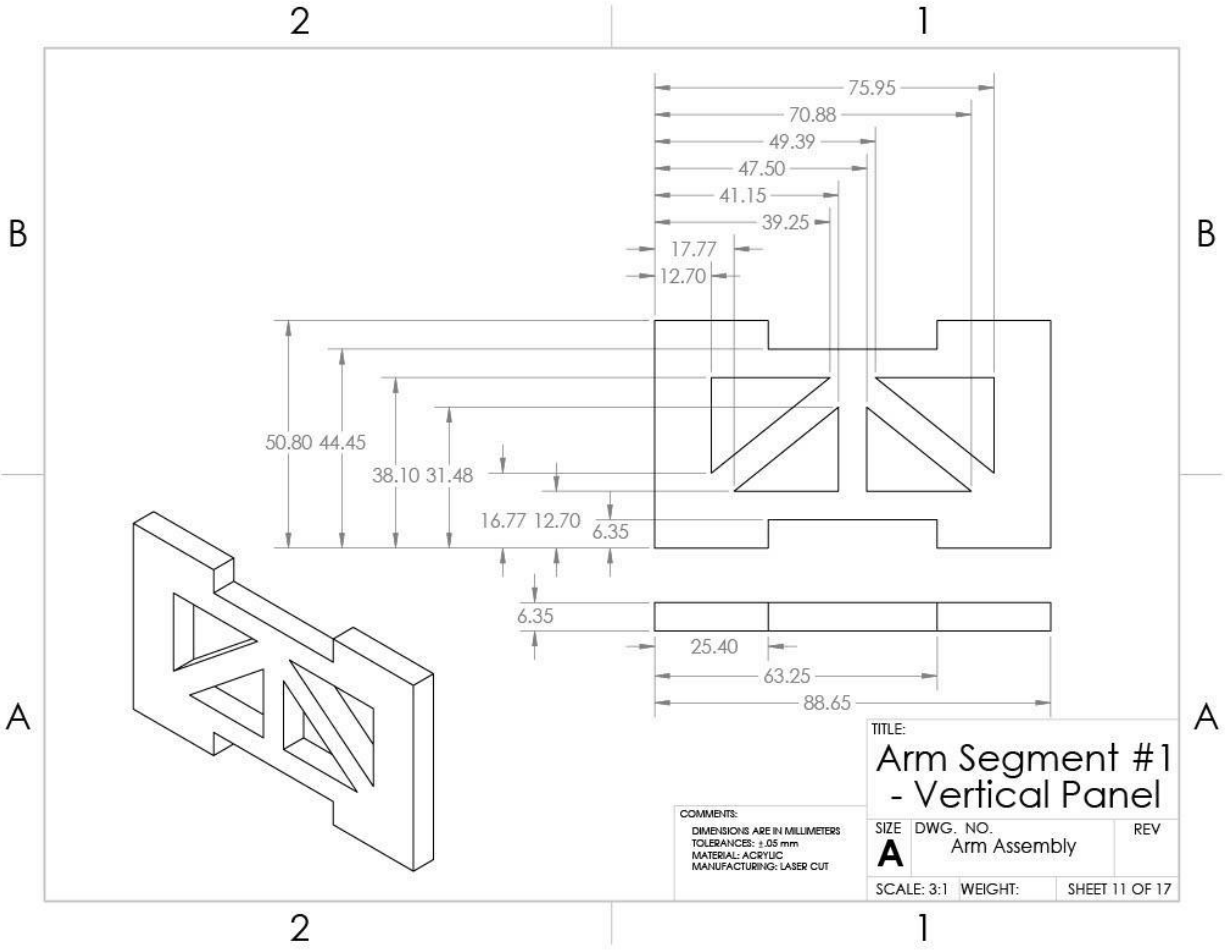
COMMENTS:
 DIMENSIONS ARE IN MILLIMETERS
 TOLERANCES: ± 0.05 mm
 MATERIAL: PETG
 MANUFACTURING: 3D PRINT

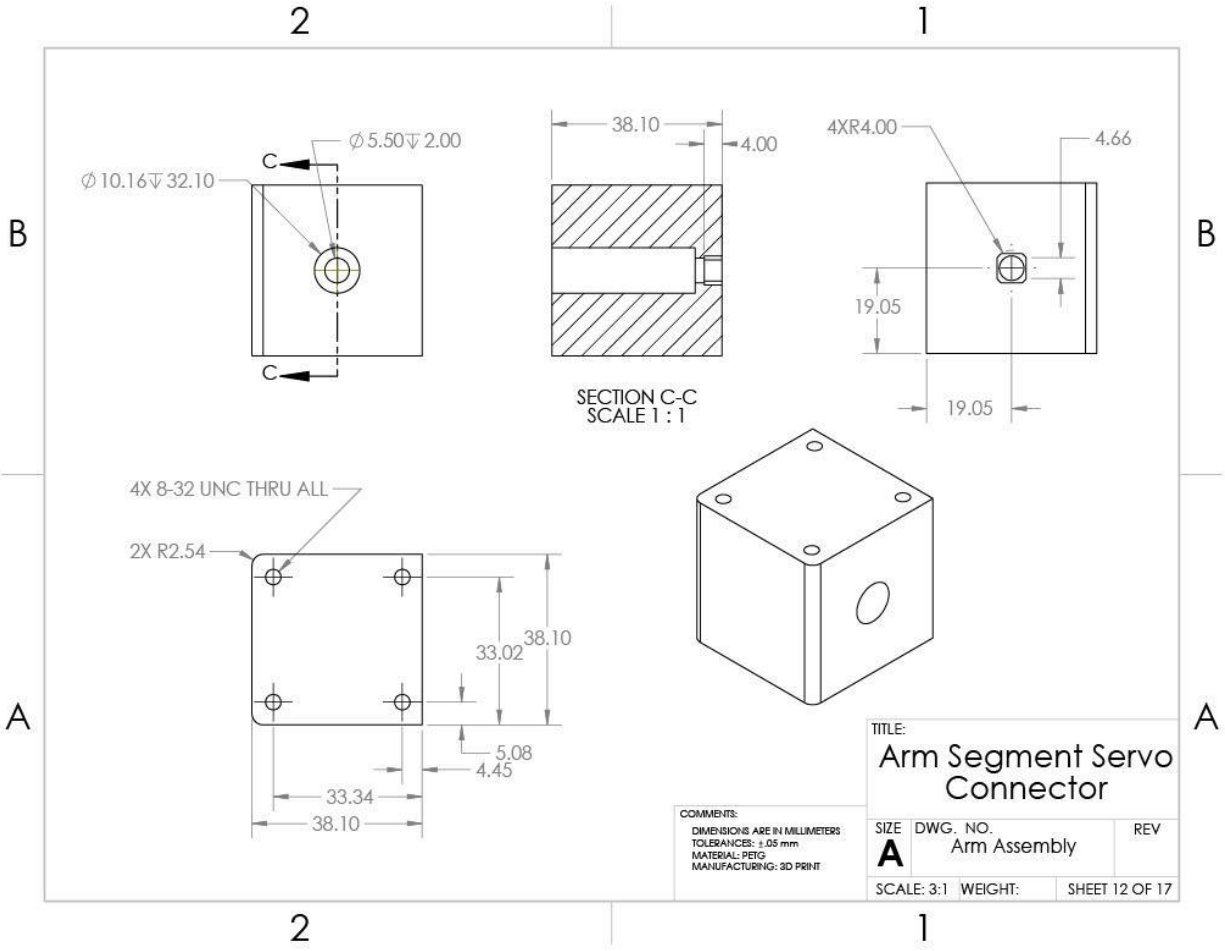


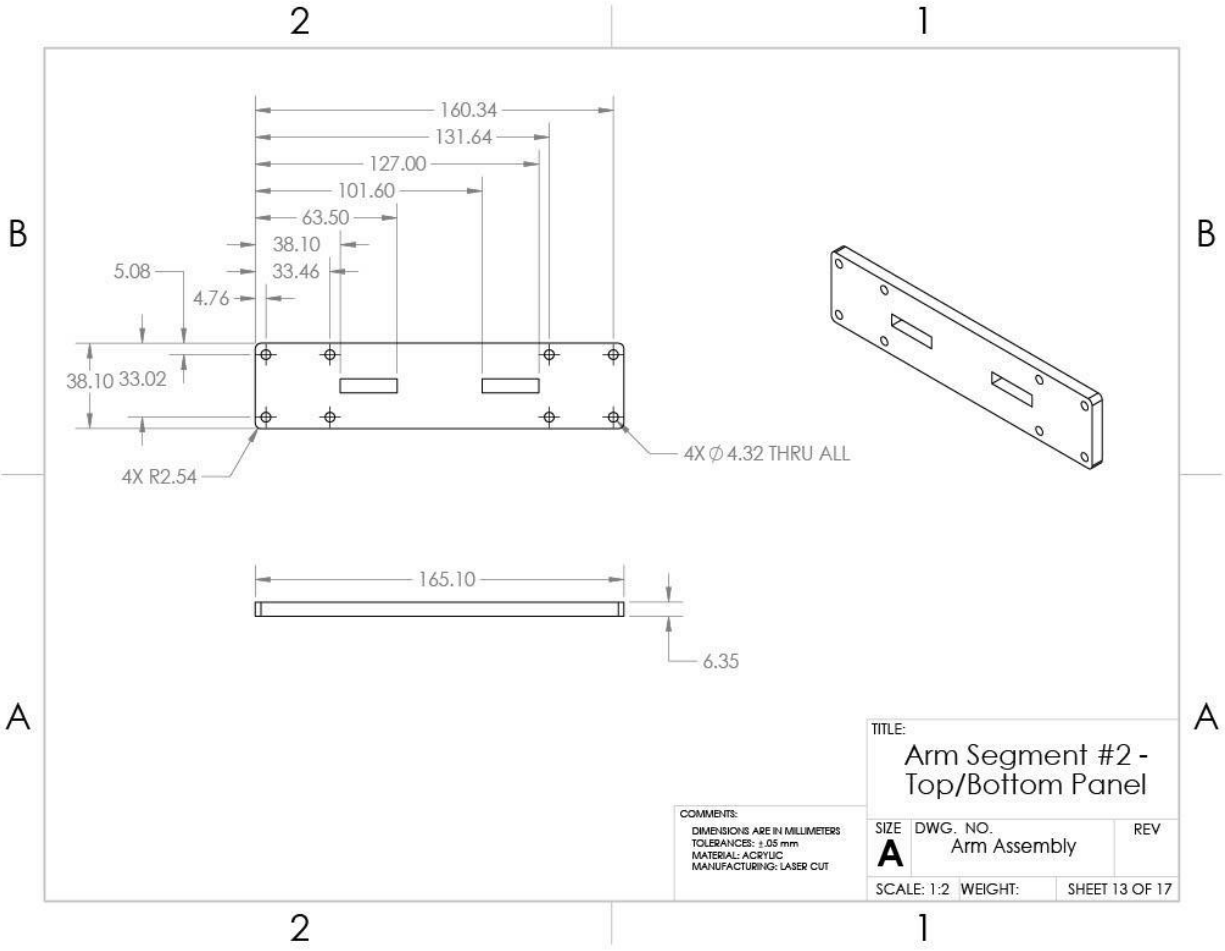
TITLE:		
Arm Segment #1 - Bottom Panel		
SIZE	DWG. NO.	REV
A	Arm Assembly	
SCALE: 1:2	WEIGHT:	SHEET 9 OF 17

COMMENTS:
 DIMENSIONS ARE IN MILLIMETERS
 TOLERANCES: ± 0.05 mm
 MATERIAL: ACRYLIC
 MANUFACTURING: LASER CUT



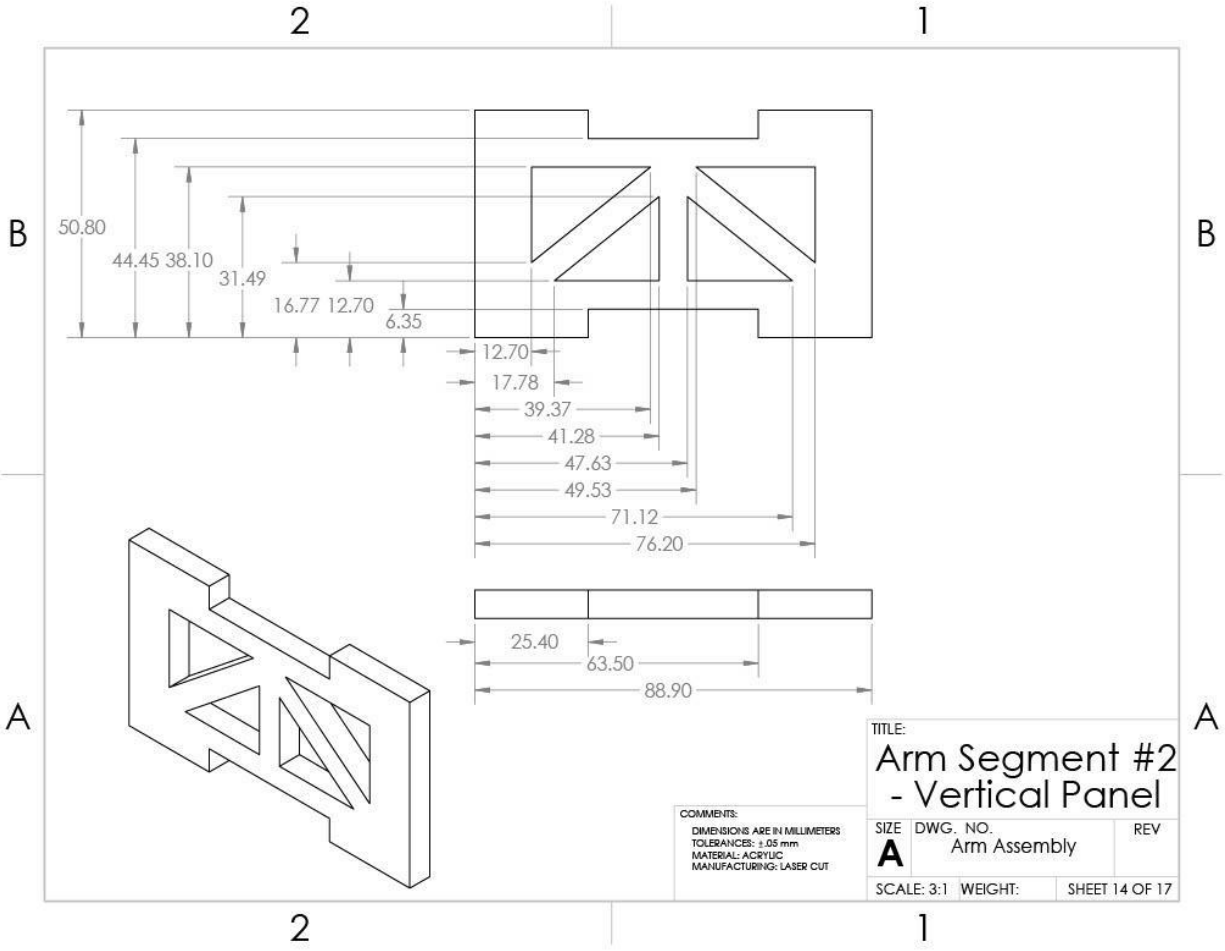


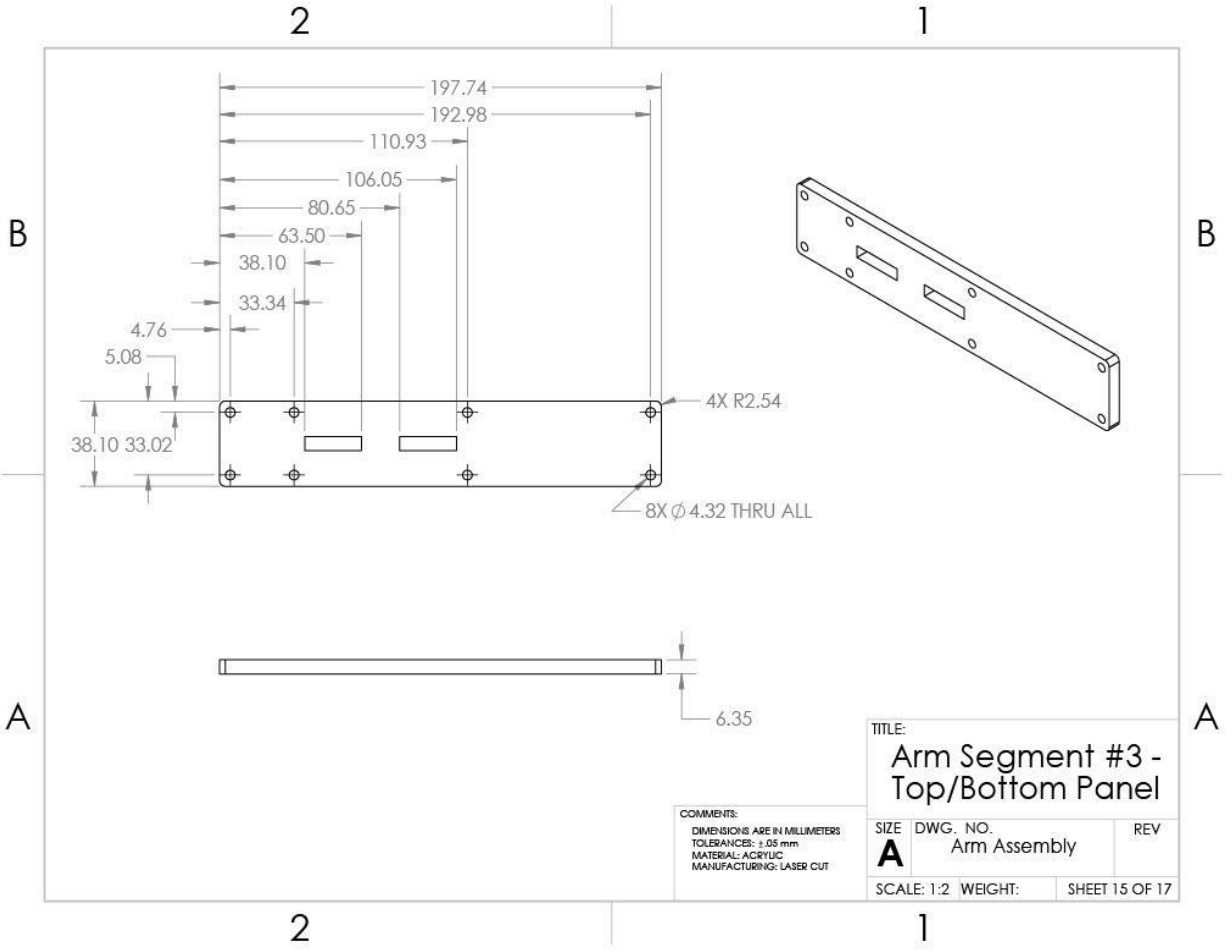




COMMENTS:
 DIMENSIONS ARE IN MILLIMETERS
 TOLERANCES: ± 0.05 mm
 MATERIAL: ACRYLIC
 MANUFACTURING: LASER CUT

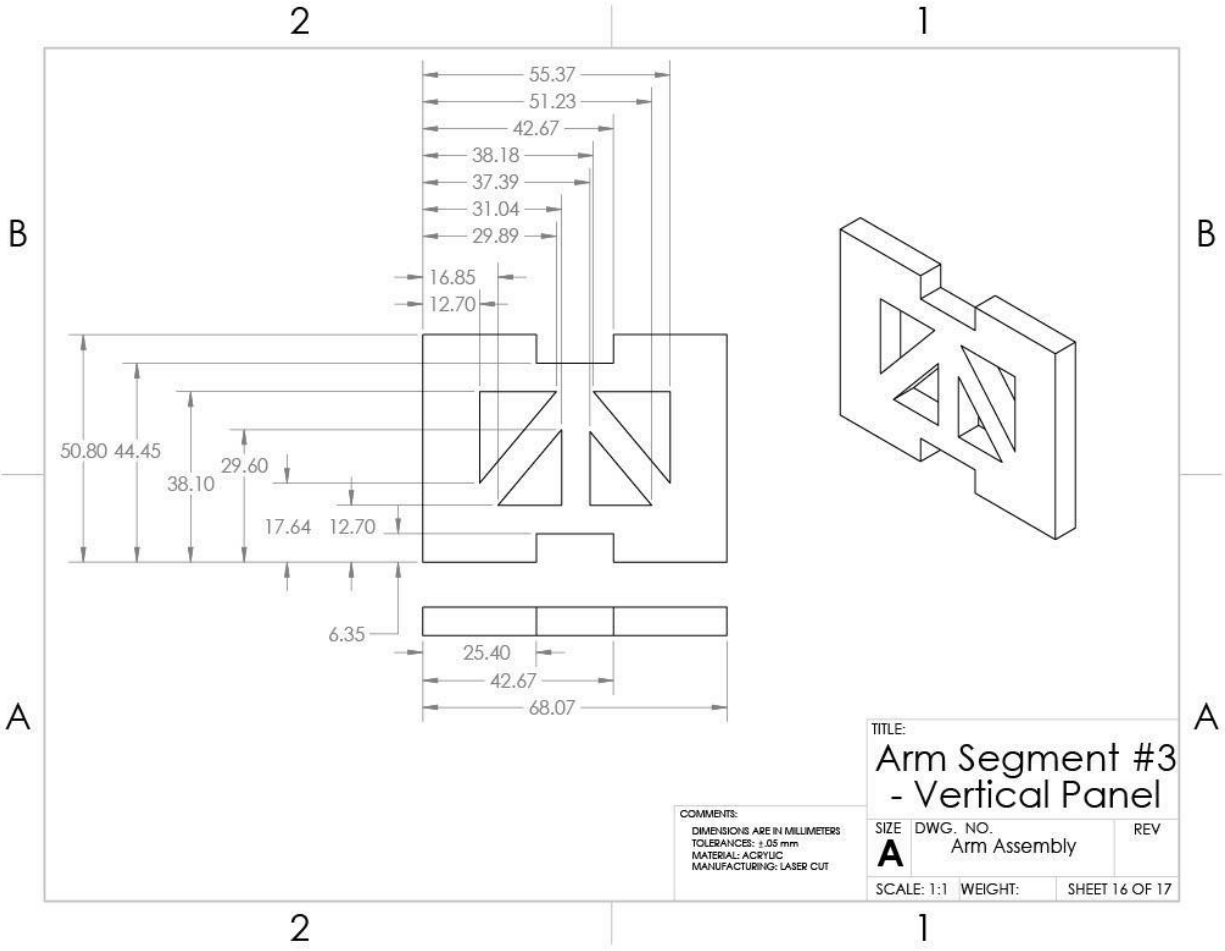
TITLE: Arm Segment #2 - Top/Bottom Panel		
SIZE A	DWG. NO. Arm Assembly	REV
SCALE: 1:2	WEIGHT:	SHEET 13 OF 17

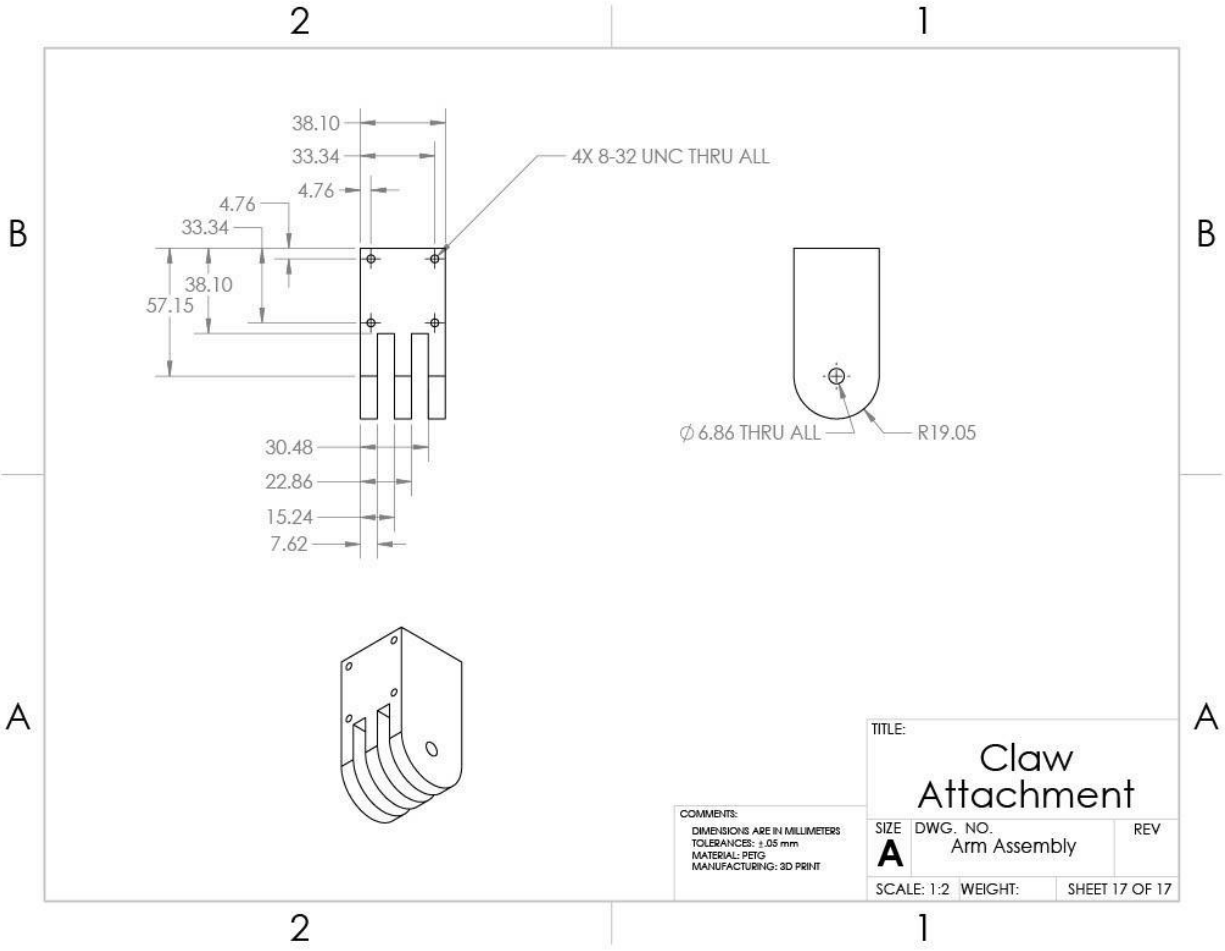




COMMENTS:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES: ± 0.05 mm
MATERIAL: ACRYLIC
MANUFACTURING: LASER CUT

TITLE: Arm Segment #3 - Top/Bottom Panel		
SIZE A	DWG. NO. Arm Assembly	REV
SCALE: 1:2	WEIGHT:	SHEET 15 OF 17





Appendix H: Key Source Code

```
bool Parser::read_stog(){
    return this->_stog;
}

int8_t Parser::read_camdir(){
    return this->_camdir;
}

int Parser::read_servo1() {
    return this->servo1;
}

int Parser::read_servo2() {
    return this->servo2;
}

int Parser::read_servo3() {
    return this->servo3;
}

int Parser::read_servo4() {
    return this->servo4;
}

int Parser::read_servo5() {
    return this->servo5;
}
```

Initiating the read functions for each servo

```

    case 10:
        strcpy(tokens10, field_ptr);
        this->servo1 = atoi(tokens10); // Servo 1
        break;
    case 11:
        strcpy(tokens11, field_ptr);
        this->servo2 = atoi(tokens11); // Servo 2
        break;
    case 12:
        strcpy(tokens12, field_ptr);
        this->servo3 = atoi(tokens12); // Servo 3
        break;
    case 13:
        strcpy(tokens13, field_ptr);
        this->servo4 = atoi(tokens13); // Servo 4
        break;
    case 14:
        strcpy(tokens14, field_ptr);
        this->servo5 = atoi(tokens14); // Servo 5
        break;
    case 15:
        strcpy(tokens15, field_ptr);
        break;
    default:
        strcpy(tokens0, "DEFAULT OOPS");
        break;
}

} //end parsing for loop

```

Copying servo values from their respective tokens to be parsed on the subsea side

```

class Parser{
public:
    Parser();
    void parse(char* data);
    int is_valid();
    uint32_t read_ackid();
    float read_thrusters(uint8_t index);
    int read_ltog();
    bool read_stog();
    int8_t read_camdir();
    char read_ltogop();
    int read_servo1();
    int read_servo2();
    int read_servo3();
    int read_servo4();
    int read_servo5();
    char ltogop1[10];
    float ltogop2,ltogop3, ltogop5, ltogop6;
    int ltogop4;
    float find_max(float,...);
    float find_max_thruster(float floatarray[], int start, int end);
    float find_max_thruster_closed(float floatarray[][1], int start, int end);
    float find_max_scaling(float float1, float float2, float float3);
    void multiply_matrices(float first[][3], float second[][1], float result[][1], int r1, int c1, int r2, int c2);

```

Parser class that stores all the token values for a given NMEA string and processes them

```

#prepare necessary resources for second gamepad
if config.gamepad2_flag:
    global gamepad2
    print("second gamepad initializing...")
    #second gamepad initialization
    generate_dictionaries("map2.txt")
    gamepad2 = Gamepad()
    config.gamepad2_flag = gamepad2.init(1)
    print("second gamepad initialized")

```

Code to initiate second gamepad if gamepad2 flag is set to 1


```

CAM_RATE = 1
INPUT_RATE = 500
PROCESS_RATE = 100

THRESHOLD = 0.1

gamepad_flag = True
gamepad2_flag = True
cam_flag = False
socket_flag = True
altitude_lock_flag = False

top_data = Data(["FORWARD", "RIGHT", "BACK", "LEFT",
                "DOWN", "UP", "ROT_CCW", "ROT_CW", "S_TOG",
                "L_TOG", "CAM_UP", "CAM_DN"])
sub_data = Data(["ID", "TMPR", "DEPTH", "HEAD", "ALT"])

arm_inputs = Data(["S1_LEFT", "S1_RIGHT",
                  "S2_FORWARD", "S2_BACK", "S3_FORWARD", "S3_BACK",
                  "S4_OPEN", "S4_CLOSE", "S5_CW", "S5_CCW"])

map_dict = None
map2_dict = None

```

Config file that has flag values, global fixed variables, and the field names for the ROS to parse

```

def generate_dictionaries(filename):
    #gamepad_dict
    #for each line in map.txt
    #create a dictionary entry: 'VAL_NAME : BUTTON_NAME'

    filepath = "packages/gamepad/" + filename

    # create gamepad2's dict if gamepad's dict is already created
    # we only want to generate gamepad2's dict if gamepad's dict is already created
    if config.gamepad2_flag and config.map_dict != None:
        if config.map2_dict != None:
            return
        dictionary2 = {}
        file = open(filepath, 'r')
        for line in file:
            line = line.rstrip('\n')
            split = line.split("=")
            dictionary2[split[0].strip()] = split[1].strip()
        file.close()
        config.map2_dict = dictionary2
        return

    if config.map_dict != None:
        return

    dictionary = {}

    file = open(filepath, 'r')

    for line in file:
        line = line.rstrip('\n')
        split = line.split("=")
        dictionary[split[0].strip()] = split[1].strip()

    #rint(dictionary)
    file.close()

```

Logic for when to generate gamepad2 and linking it to the dictionary for its respective mappings

```

# robot arm servo values
# reads controller values and maps them to pwm values for servos
# robot arm servo controller pins 0,2,12,14,15 from left to right servo1-servo5

mult = 30 # movement multiplier, increase mult to increase servo speed

servo1 = arm_inputs.read("S1_LEFT") - arm_inputs.read("S1_RIGHT")
s1_mapped += (servo1 * mult)
if (s1_mapped < 10):
    s1_mapped = 10
elif (s1_mapped > 420):
    s1_mapped = 420

#s1_mapped = round(map(servo1, -1,1, 10, 420), 1)

servo2 = arm_inputs.read("S2_FORWARD") - arm_inputs.read("S2_BACK")
if (s2_mapped > 30 or s2_mapped < 380): s2_mapped +=(servo2 * mult)
if (s2_mapped < 10):
    s2_mapped = 10
elif (s2_mapped > 420):
    s2_mapped = 420

#s2_mapped = round(map(servo2, -1,1, 10, 420), 1)

servo3 = arm_inputs.read("S3_FORWARD") - arm_inputs.read("S3_BACK")
if (s3_mapped > 30 or s3_mapped < 380): s3_mapped += ((servo3 + 0.5) * 2 * mult)
if (s3_mapped < 10):
    s3_mapped = 10
elif (s3_mapped > 420):
    s3_mapped = 420

#s3_mapped = round(map(servo3, -1,1, 10, 420), 1)

servo4 = arm_inputs.read("S4_OPEN") + arm_inputs.read("S4_CLOSE")
if (s4_mapped > 110 or s4_mapped < 200): s4_mapped += (servo4 * mult)
if (s4_mapped < 100):
    s4_mapped = 100
elif (s4_mapped > 200):
    s4_mapped = 200

```

Taking raw joystick values for respective servos and then mapping them between -1 to 1

```

#s4_mapped = round(map(servo4, -1,1, 100, 200), 1)

servo5 = arm_inputs.read("S5_CW") - arm_inputs.read("S5_CCW")
s5_mapped = 0
#s5_mapped += (servo5 * mult)
#if (s5_mapped < 10):
#    s5_mapped = 10
#elif (s5_mapped > 420)
#    s5_mapped = 420

#s5_mapped = round(map(servo5, -1,1, 0, 0), 1)

output = add_next(output, str(round(s1_mapped)))
output = add_next(output, str(round(s2_mapped)))
output = add_next(output, str(round(s3_mapped)))
output = add_next(output, str(round(s4_mapped)))
output = add_next(output, str(round(s5_mapped)))

#end of string
output = add_next(output, '*')

#print(output)
ack_id = ack_id + 1

return(output)

```

Adding the calculated servo values to the NMEA string

```

S1_LEFT = JOY1_LT
S1_RIGHT = JOY1_RT
S2_FORWARD = JOY1_UP
S2_BACK = JOY1_DN
S3_FORWARD = JOY2_UP
S3_BACK = JOY2_DN
S4_OPEN = R2_ANLG
S4_CLOSE = L2_ANLG
S5_CW = CIRCLE
S5_CCW = TRIANGLE

```

Dictionary of mappings from our controller values the ROS processes to the values the controller library uses