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Nautilus ROV Robot Manipulator

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SANTA CLARA UNIVERSITY

Department of Mechanical Engineering
and
Department of Computer Science and Engineering

I HEREBY RECOMMEND THAT THE THESIS PREPARED
UNDER MY SUPERVISION BY

Dana Stefanides, Jenny Huynh, Andrew Stewart, Steven Reimer, Andrew Nguyen, Rebecca Walters, and Matt Hayes

ENTITLED

NAUTILUS ROV ROBOT MANIPULATOR

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

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NAUTILUS ROV ROBOT MANIPULATOR

By

Dana Stefanides, Jenny Huynh, Andrew Stewart, Steven Reimer, Andrew Nguyen, Rebecca Walters, and Matt Hayes

SENIOR DESIGN PROJECT REPORT

Submitted to
the Department of Mechanical Engineering
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of

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in Partial Fulfillment of the Requirements
for the degree of
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Abstract

Global warming and climate change are prevalent issues in today's society. As a result, research in the ocean, our world's biggest ecosystem, is imperative in efforts to protect the environment. Santa Clara University's Robotic Systems Lab contributes to this field through work and developments on remotely operated vehicles (ROVs). An existing ROV system called Nautilus consists of a robot arm, end effector, and storage system in order to collect various types of sediments at a depth of 300 feet. However, the previous system does not meet that requirement. In direct collaboration with researchers within the Monterey Bay Aquarium Research Institute, we were able to create and accomplish a set of deliverables to improve our ROV. Our team's main goal was to make the system functional and more efficient by redesigning the manipulator arm and soft gripper in order to retrieve samples, as well as creating a sample storage container that is in view of the camera or workspace to document and record the location of those samples. Our project gives researchers a cheaper alternative compared to existing sample collection methods, which are relatively more expensive, so that they can continue to explore and document stretches of the ocean far more easily.

The project was done with the guidance of faculty in the Robotic Systems Lab as well as researchers from the Monterey Bay Aquarium Research Institute (MBARI).

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Section 1: Introduction

1.1 Background and Motivation

October 10th, 2022 marked the beginning of the annual tUrn week event at Santa Clara University which hosts speakers to educate students and faculty on key topics within the current climate crisis. Director of tUrn, Kristin Kusanovich, opened the event with a presentation on Seven Ideas for Collectivism in which she promoted the pursuit of personal climate leadership. Within this most pivotal decade of the climate crisis, it is essential that we make environmental justice a priority. Kusanovich's fourth bullet of accessible climate leadership states, "if we do not talk about it, then it will never get solved" [1]. However, discussions alone will not solve the climate crisis without the necessary corresponding actions.

Moreover, environmental conservation is a religious obligation as well as a personal responsibility. In his work, "The Case for Catholic Support: Catholic Social Ethics and Environmental Justice," Bryan N. Massingale uses conceptual and empirical research to build his undeniable thesis that climate justice is a Catholic moral responsibility. Most notably, Massingale highlights the fundamental human right to a safe environment in which God has endowed all humans regardless of their economic status, race, or sex [2]. Therefore, we strive to recognize and emphasize ways in which our project aligns with Catholic Social Ethics. Within our project scope, we will be focusing on the development of marine ecosystem research through the development of affordable underwater sample collection equipment. Our project mission statement is derived from the ultimate goal of enabling better access to the tools required for continued environmental research.

Research is a critical component to understanding the current environmental status and climate crisis impacts. Regina Koltzenburg in her article, "The direct influence of climate change on marginal populations: a review," provides an overview of the existing research on terrestrial, marine, and limnic populations to discover trends and underrepresented groups. Koltzenburg concludes that there is a significant bias against research on limnic ecosystems as well as a bias towards animal studies over plant studies [3]. Thus, we position our project scope to focus on limnic ecosystems (more specifically Lake Tahoe) as well as non-animal sample collection. Looking toward the future of underwater research, a global horizon scan of marine biodiversity implies the potential benefits of developing technologies that provide higher-quality data and imaging [4]. However, there is still a need for critical examination of emerging research technologies in order to safeguard the environment from unidentified hazards. Therefore, we are committed to a continuous and rigorous examination of our project with respect to environmental ethics.

1.1.1 Underwater Robotics

There are many kinds of underwater robotics systems, each performing different tasks. Underwater robotics can be split into two distinct categories: remotely operated vehicles (ROVs), and autonomous underwater vehicles (AUVs). Both can house a number of different sensors and are customized to specific mission parameters. Underwater robotics provides scientists with the ability to view and collect data from places where humans could never go, allowing for unique breakthroughs in marine research. Still, underwater robotics technology is relatively new and there is much research and development to be done.

To start, we look at the different applications of these marine vehicles. ROV sizes can range from that of a laptop to that of a pickup truck [5]. They are taken out on boats and are lowered into the water by hand or by crane, as necessary. A long tether spans from the ROV to the control station, allowing for constant communication throughout the deployment. Typically, a video feed is relayed from the ROV to this command station in real-time. This allows the ROV to be piloted from the boat, giving them the freedom to explore the area and potentially collect samples of interest.

AUVs, on the other hand, act independently from human control during a deployment. As such, there is no tether connecting the vehicle back to a command station, requiring that they are fully autonomous (able to function with zero or limited user input). AUVs are fully complete systems, containing all necessary software and hardware to complete a mission unassisted. They collect and store data while underwater, then transfer that data to scientists after returning to the surface. AUVs pose specific advantages to scientific research because they are not limited by a tether, thus expanding their range.

Both AUVs and ROVs are important cutting-edge robotics tools currently being used to gather data and make discoveries in our planet's oceans, lakes, and rivers. Each has specific characteristics that make it suitable for different applications. Nautilus, the vehicle used in this project, is an ROV. All commands are sent down via a tether from a topside command station.

Similarly, our robot manipulator system will also be controlled remotely from the command station.

1.1.2 SCU RSL and Research Facility

The Robotics System Lab (RSL) at Santa Clara University has lots of experience in the marine robotics field. RSL has worked with commercially available ROVs (BlueRov from Blue Robotics), custom ROVs (Triton, Tessie, and Nautilus), vertical profilers, and custom AUVs (like MOANA).

Triton was the RSLs first ROV and was designed to do research in Lake Tahoe. This ROV was quite large, weighing over 250 lbs., making it quite challenging to maneuver and transport. Nautilus was then made a year later (2000), designed as a smaller version of Triton. Weighing only 180 lbs., Nautilus was easier to operate, but it could not reach Triton's maximum depth of 2000ft. As marine robotic technology continued to develop, Blue Robotics launched their Blue ROV, a commercially available ROV even smaller than Nautilus. As such, 2016 marked the RSL's construction of Tessie, the smallest ROV in the lab's arsenal.

In other marine research, RSL has mainly focusing on vertical profiling. Vertical profilers are autonomous robots that descend a column of water and then return to the surface, capturing data on a vertical gradient. In addition, the lab has dabbled in AUVs recently building MOANA, a large AUV spanning over 8 feet.

All of this marine robotic experience within this laboratory critical to mention because it is invaluable to our team and our project. These decades of experience, passed on by faculty advisors, help us understand the challenges of underwater robotics and aid in establishing a realistic project scope. Additionally, this research allows for industry connects at organizations such as the Monterey Bay Aquarium Research Institute (MBARI). Here, scientists and engineers have provided insight and advice into the field of marine robotics as well as access to their testing facilities.

1.2 Statement of Goals

Guided by research, interviews, the shortcomings of last year's design, and guidance form faculty advisors, the goals for the group are focused on producing a working prototype of a marine robot arm and storage system by the end of the school year. The scope has been sized carefully to make sure a working system is achievable.

1.2.1 Mission Statement

Develop a novel prototype manipulator system for the Nautilus underwater robot.

1.2.2 Expanded Thesis

Success within our project can be evaluated according to our system requirements documentation based on our mission objectives to create a controllable underwater manipulator system. The final manipulator system will consist of an arm, end effector, and storage system with key innovations including soft gripping capability and Cartesian endpoint control. Our system will be designed to grasp delicate rock samples of approximately 2”x2”x2” dimensions off of the seafloor with only the view of a single front-facing camera. Our gripper will achieve soft-gripping capability through mechanical design which avoids the necessity for additional sensors. The system must then be able to place the rock sample within the designated storage compartment and collect at least three samples per dive.

Sample collection may be actuated through individual servo joint control or through Cartesian endpoint control. In addition, operation and sample collection procedures must be properly documented to allow for a smooth transition to the next team of engineers who seek to utilize the Nautilus ROV and manipulator arm. Our final system is best defined as a functional prototype, due to several limitations known to be outside our scope from the beginning of the year. While the scope of our project is limited due to time and cost constraints, we remain steadfast in our goal to contribute to the environmental research community by designing and fabricating an affordable underwater prototype manipulator system.

Section 2: System Description

2.1 Customer Needs

Despite having different positions and backgrounds, the stakeholders for this project all share a common vision for the end-of-year deliverables. Not all customer requests can be accommodated within our allotted time and budget; however, speaking with experts provides context for prevalent themes that will emerge through continued project testing and development. Both email and live Zoom interviews were conducted with marine science researchers, geologists, and field engineers from outside organizations (including MBARI). Additional consults were requested with faculty advisors, Dr. Christopher Kitts and Dr. Michael Neumann, as well as members from past Nautilus design teams. Here, our team was able to understand the most important needs of marine sampling and the most effective engineering practices that can be implemented to fulfill those needs. Subsequently, our initial project scope was developed with the main goal of accomplishing a functional final manipulator system while accounting for as many specific customer needs as possible. Ultimately, the stakeholder interview process revealed a multitude of key insights early in our design process that otherwise may not have emerged until far later in our testing.

2.1.1 Customers

First, our main stakeholder in this process is the director of the SCU Robotic Systems Laboratory, Dr. Christopher Kitts. As director of RSL, Dr. Kitts has a multitude of experiences with other ROV projects within this organization. Furthermore, he possesses invaluable contacts and facilitated the group's opportunity to interview most of the names to follow.

Dr. Michael Neumann is a long-time Santa Clara researcher and member of RSL with an emphasis on marine ROVs. He has provided oversight of RSL missions to Lake Tahoe and Monterey Bay and has helped many student groups gain insights into these ecosystems.

Bill Kirkwood is a Senior Research and Development Engineer at MBARI and has over 30 years of experience with the institute. Bill has developed a number of vehicles and instruments at MBARI including several underwater ROVs similar to Nautilus. He is also an adjunct professor within Santa Clara University's Mechanical Engineering Department.

Thomas Adamek is another talented researcher and marine engineer who formerly worked in the RSL. Aside from his technical expertise, he has tons of experience with underwater ROVs and their deployment processes.

Finally, Dr. Rich Schweickert is an emeritus from the University of Nevada Reno who has worked with RSL and Dr. Kitts for multiple decades. Dr. Schweickert is a geologist who makes frequent trips to Lake Tahoe with interests in research based on video of the lake's bottom.

2.1.2 Interviews

Our stakeholder questions revolve around three different themes and are as follows. What types of samples do you want to pick up? How are those specific decisions made during the mission? What are common engineering successes/pitfalls in the underwater ROV design process? While both our faculty advisors could provide general guidance in all these areas, each outside interviewee gave specific insight regarding what types of things would be beneficial to incorporate into the robot arm and storage system.

During our time with Bill Kirkwood, we focused on the first two categories. It was necessary to find out the common practices used to perform marine research as well as the particular specimens of interest. He mentioned that for MBARI specifically, using a robot arm with an end effector suited to lift a "T" bar is common for moving and placing different instruments on the seafloor. Each instrument typically has the standardized ability to work with such an end effector. Additionally, he outlined the different materials that would be of interest to bring back to the surface. When dealing with silt and mud, it is most desirable to use a push corer that inserts into the sea floor, making the different layers visible. With this, it was clear that simply scooping up mud or silt serves no real purpose. Furthermore, simple rock pieces or other specimens less than the size of a fist are also of interest to the institution. That is, only if each sample is kept organized in a storage system with the location of the collection documented. Additionally, choosing what specimens to collect while on a mission is critical due to limited space. Size and color are important, yet difficult to gauge due to the limited light in a marine environment. As such, Bill suggested a color band attached to the robot arm that can be seen in the camera's view. This way, colors can be compared and determined from the band. Aside from judgment of the camera image, size can be more tricky, especially in turbulent water. Here, a parallel laser system was mentioned as a possible solution. Finally, we discussed the storage system. There are tons of workable systems that MBARI uses, most of which prioritize needs not associated with this project. The most pertinent requirement here is the fact that a blind drop of the sample into the storage container is unacceptable. Losing the sample due to a bad drop could render the whole mission useless.

More on the engineering side, Thomas Adamek provided insight from the multiple underwater ROVs he has experience with. In regard to the arm itself, we talked at length about whether or not to make the arm strong enough to operate out of water, as this would make testing much easier. The conclusions, however, fell on maintaining focus on our specific project tasks to design a lightweight, neutrally buoyant design that is only operable underwater. Thomas recognized the negative effects for testing purposes, but he warned that there is a more important parameter that is in play here. Maintaining the overall balance and positive buoyancy of the Nautilus itself is more fundamental to the mission. Keeping the robot arm neutrally buoyant will not disrupt the movement of Nautilus and will aid the actual application of the robot arm. He added that different puppeteering ideas (strings or rubber bands) could be implemented to make above-water testing possible for such a robot arm.

Finally, Dr. Rich Schweickert was interviewed later in the conceptual design process, and he largely reiterated needs vocalized by Bill Kirkwood and our two faculty advisors. He mentioned that at Lake Tahoe, hard rock (with a width of roughly 3 inches), such as granite or volcanic rock, are of interest to his research. Furthermore, documentation such as location and context are just as critical as the specimen itself. Here, context refers to the state of the specimen as it was found (laying on the sand, etc.). Dr. Schweickert also agreed with the importance of collecting more than one sample on a given mission.

2.1.3 Customer Needs Implementation

After compiling all of our research, interview notes, and counseling from faculty advisors, the group put together a comprehensive vision for the scope of the project. Table 2.1 below was used to see what categories of marine research we wanted to tackle, and what requests would be left for future work. In sum, the group designed and built a multi-DOF robot arm with a soft-gripping end effector. The purpose of this arm system is to pick up small (2x2x2 inch) rocks on the ocean floor and place them into a storage system with multiple compartments. Viewing the sediment layers through the use of a push corer is not a part of our scope. A static, end effector designed to lift a “T” bar was also designed to establish mechanical modularity.

Table 2.1: Customer needs and associated importance (out of 5)

Customer Needs	Imp.
Able to collect rocks, mud, and silt (various types of sediment)	5
Collect and store multiple samples on one excursion	5
Timely (collect multiple samples in the span of a 45-minute mission)	4
Samples up to the size of a hand	5
See the layering in a couple of inches of sediment (push core)	3
Able to move and place marine instruments through the use of a “T” handle	4
Function at a depth of 300ft (reach non-diveable depths)	4
Ability to break off thin rock layers	3
Accurately identify and record coordinates of where a sample has been taken	5
Compatibility with existing tools	3
Able to move and place instruments on sea floor	3
Nominal effects on ROV’s motion, stability, and neutral buoyancy	5
Visual readings of ROV’s distance from the ground on decent	2
Ability to identify size and color of things seen in the camera	3
Manipulator system is fully removable/storable/transportable	3
Thorough documented procedures from attaching, using, removing and storing	4
Takes less than 3 tries for a trained user to achieve a given task	3
System is user-friendly/not overly complicated to control	3

2.2 System Requirements

The next step in the design process was verbalizing a series of system requirements with specific, numerical design parameters. System requirements are critical to the design process as they allow for specific testing and verification to ensure all mission objectives are satisfied. The requirements are structured so that each variable can be individually tested/traced back to mission objectives. The first requirements in the section below are the most important to a fully functional system, while the others are goals for the system. Some of the numerical ranges are initial estimations, while others were decided upon through research of similar systems.

List of Requirements:

1. **Sample Collection**
   - Pick up and hold samples of unusual geometries between 3 and 8 in^3 without dropping.
2. **Joint Control**
   - Center the end effector directly above the sample ± 3 in. within 3 attempts.
3. **Endpoint Control**
   - Maneuver the end effector to a specific point in Cartesian coordinate space ± 3 in.
4. **Sample Storage**
   - Deposit the sample in the intended storage compartment with > 90% success.
   - Storage container can hold up to 3 samples in separate, closed sections.
5. **Workspace**
   - Arm must utilize a working area > 1.5 ft^2. Entire workspace and storage compartment must be visible through camera view.
6. **Soft-Gripping Capability**
   - The gripper actuator must apply a force between 4 and 7 Newtons.
   - The gripper actuator applies a force of less than 12 MPa.
7. **ROV Balance**
   - Balance and buoyancy of the Nautilus ROV must not be affected by the robot arm and storage system.
   - The robot arm must be neutrally buoyant.

8. **ROV Buoyancy**
    - System must be slightly back-heavy (to reduce the impact of sand/sediment getting in the storage system (OR) System must be back-heavy by 30 degrees when the arm is in a stored position within the ROV frame.
    - Extending the arm through ROM must not affect the front-to-back buoyancy of the ROV by more than 25 degrees.
9. **Arm Speed**
    - End point of the arm must not move faster than 1 m/s.
10. **Gripper Speed**
    - Gripper must not take less than 3 seconds to close once grasping actuation has begun.
11. **System Controls**
    - Arm controls must be operational for a single person while on mission (not the person operating the ROV).
    - Arm will be controlled using joystick signaling of endpoint velocities.
    - The gripper is opened and closed with a single button/key.
    - The storage system is pushed into the view of the camera with a single button/key.
12. **Arm Housing**
    - Add a slice of framing off the front of the Nautilus ROV to house the robot arm when not in use.
    - The arm must have a home position that protects all appendages by stowing within the framing extension.
13. **Loss Prevention**
    - ROV must maintain a slight positive buoyancy.
    - The tether must be strong enough to drag ROV without breaking in case of power loss.
14. **Robot Arm Software**
    - Software must accommodate both a joint-oriented and endpoint-oriented approach for specifying arm movement commands.
    - Joint controls allow the user to specify the rotation of the servo at each joint.

- Endpoint controls mean the arm moves to a location through a coordinate system.

15. Documentation

- When a collection is made, the location of the sample is documented.

16. Color Wheel

- Colored bands are attached to the robot arm in view of the camera.

17. Laser

- A laser or light extends from the end effector to see what is directly below.

18. Workspace Size

- The arm must be able to collect samples from a workspace that is at least 1 square foot in the seafloor plane.

19. Debris

- The robot arm and gripper must maintain functionality despite the presence of sand/silt/mud floating in the water.
- Motors/actuators must be shielded from such debris.

20. System Modularity

- The current modularity of the ROV structure, thrusters, electronics, and all other maintained components must at least be maintained at its original state.
- The arm must be able to separate from the ROV.
- The arm housing must be able to separate from the ROV.
- The storage system must be able to separate from the ROV.
- The end effector must be able to separate from the arm.
- Software must be clear and understandable for future modifications and access.
- Software must allow for future integration of additional end effectors.
- Electronics must allow for the future integration of additional end effectors.

2.3 System Overview

Figure 2.1 below is a concept of operations diagram depicting the basic operations of the entire Nautilus system. Up until this point, the Nautilus ROV has solely been used to view things on the ocean floor. It is lowered into the water using a crane on the boat, and the four propellers force the ROV to descend. Nautilus is positively buoyant, meaning that shutting off the thrusters (or even a loss of power) results in the ROV returning to the surface on its own. After the descent, the current system is only capable of viewing things on the lake or ocean floor. After our project is complete, the ROV will be fitted with a robot arm, end effector, and storage system as sketched in Figure 2.1. Once the ROV reaches maximum depth, a controller from above the surface can send commands through the ROV's tether to operate the robot arm, grab marine specimens, and place them in the storage system. After the collection is complete, the location and context of the sample are recorded, and the ROV can move on to another area. This process can be repeated up to three times before the storage system is full and the ROV must return to the surface.

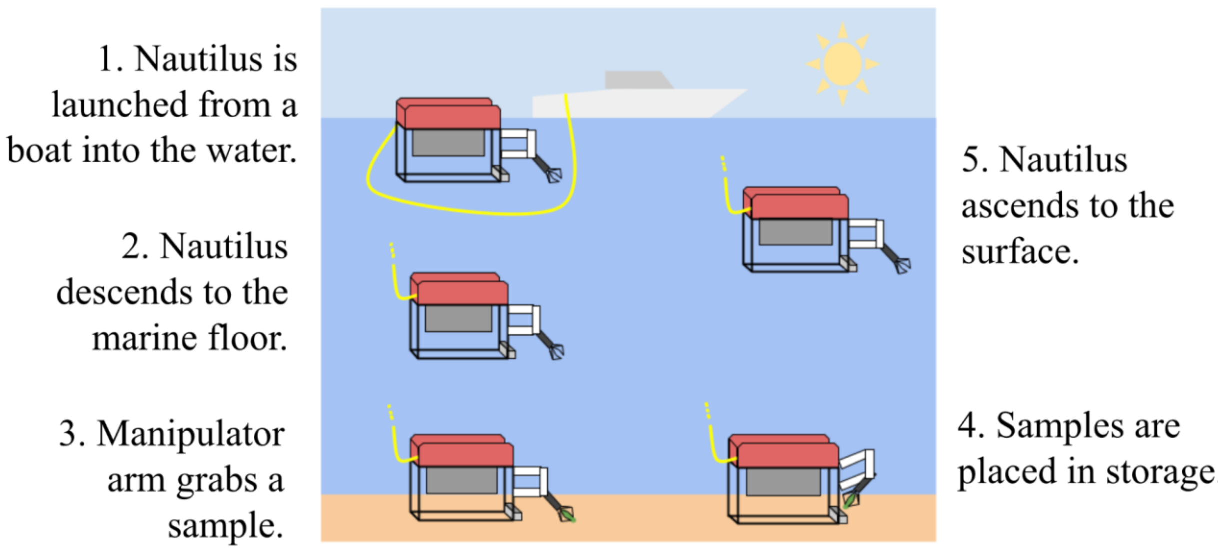


Figure 2.1: Concept of operations diagram

2.4 Procurement

The initial budget for this project makes use of the $500 given to each student by Santa Clara University's School of Engineering. Additional tools and prototyping materials were obtained in conjunction with RSL. Ultimately, we were able to re-use certain items from last year's group, resulting in a final total that is significantly under budget.

Table 2.2: Final Procurement

Item	**Quantity**	**Cost Per**	**Total Cost**
Connecting Rod, 12" Length	2	18.05	36.1
Rod End Bolt	2	22.8	45.6
Nylon-Insert Locknut	1	6.4	6.4
Socket Head Screw, 1/4"-28 Thread, 2-3/4"	1	23.91	23.91
Socket Head Screw, M3 x 0.5 mm, 22mm	1	5.45	5.45
Hex Nut, M3 x 0.5 mm	1	4.73	4.73
Nylon-Insert Locknut, 1/2"-20 Thread Size	1	8.64	8.64
Connecting Rod 6" Length	5	8.55	42.75
Button Head Hex Drive Screw,	1	8.19	8.19
Hex Nut, 1/2"-20 Thread	1	4.06	4.06
Hex Nut, 1/4"-28 Thread	1	3.56	3.56
Socket Head Screw, 1-3/4" Long	1	24.87	24.87
Socket Head Screw, 1" Long	1	31.37	31.37
Aluminum Connecting Rod	2	5.94	11.88
Spare O-Ring Set, 4"	1	3	3
Stainless Steel Hex Nut, 1/2"-13 Thread	1	3.35	3.35
Form 2 Resin Tank	1	59	59
Laser	2	69.95	139.9
SER-2020 Servo (replacement)	1	495	495
Programmer	1	22.99	22.99
Flat Surface Bracket	1	4.03	4.03
1/4" - 20 Screws	1	34.74	34.74
1/4"- 20 Nuts	1	3.15	3.15
1/4" Washers	1	8.51	8.51

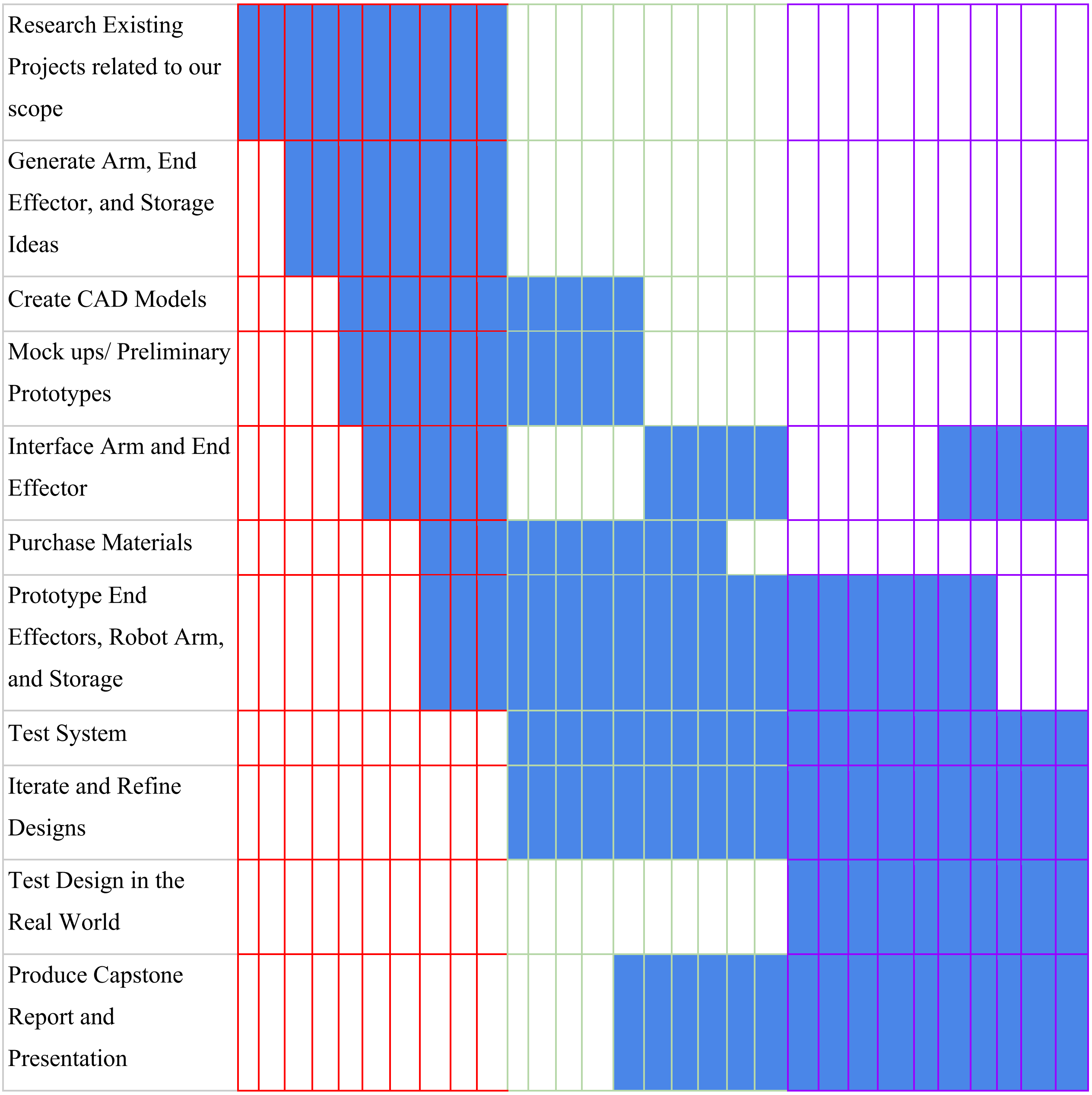
Corner Bracket	2	2.59	5.18
Thumb Screw 8-32	1	16.38	16.38
8-32 Nut	1	1.92	1.92
8-32 Washers	1	4.11	4.11
		Grand Total	**$2306.12**

2.5 Timeline & Team Management

Organization was critical with a large, 7-member senior design team. Diligent notes were taken during our weekly meetings and shared with everyone afterwards. More importantly, a list of clear action items was made for each week. Each task had target completion dates and the person responsible for completing the action. This was immensely helpful in keeping the project on track. Additionally, assignments in our Mech 194-196 classes maintained focus on the project trajectory as a whole. In general, the group never felt behind in any step of the process.

Table 2.3: Gantt chart for project timeline

	Q1										Q2										Q3									
TASK	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Interview MBARI specialists regarding specific customer needs		■	■	■	■	■	■																							
School of Engineering Funding Proposal				■	■																									
Outline of Report Section 1					■	■	■	■																						
Get Nautilus ROV Operational					■	■																								


Research Existing Projects related to our scope
Generate Arm, End Effector, and Storage Ideas
Create CAD Models
Mock ups/ Preliminary Prototypes
Interface Arm and End Effector
Purchase Materials
Prototype End Effectors, Robot Arm, and Storage
Test System
Iterate and Refine Designs
Test Design in the Real World
Produce Capstone Report and Presentation

Section 3: Soft Gripper

There are many different end effector possibilities that can be useful in marine applications. Rigid grippers, grippers with overlapping fingers, soft grippers, and claws that grab "T" bar handles all fall under this characterization. For the purposes of this project, our main deliverables are a functional soft gripper and interfacing specifications to allow for future end effector designs to be attached to the robot arm. The majority of the design process was centered around optimizing the servo actuated, soft-gripping end effector. Paired with a static claw to lift a simple "T" bar, we will demonstrate the mechanical modularity of end effectors on the robot arm.

3.1 Similar Products

In the marine robotics industry, a variety of similar products exist, all with different limitations. One example of a commercially available underwater manipulator is the Newton Subsea gripper sold commercially by BlueRobotics [6]. This gripper costs $590.00 (USD) and is able to provide a maximum gripping force of 128 N. The downside of this gripper, however, is that is it a one degree of freedom arm, meaning that positioning the arm would be incredibly challenging in a turbulent underwater environment. While this could fill a niche of collecting some samples in perfect conditions, it would be widely ineffective in collecting the vast majority of samples desired.

Another group of similar arms and arm components are produced by Reach Robotics (formerly known as BluePrint Lab) [7]. Reach Robotics offers a wide selection of different arms with different degrees of freedom, as well as different rotator components that could be used to build a robotic arm tailored to the purchaser's needs. Additionally, their products boast impressive durability, reliability, and lifting abilities of up to 2 kg. However, these advantages and variety of options come at a price. Upon requesting a quote, the price from a single rotating joint could range anywhere from $4,300-$7,300 (USD). For our minimum requirement of three degrees of freedom, such an arm would cost nearly $17,000 (USD), even before factoring in the price of an end effector and software. Ultimately, Reach Robotics products are fully capable within the environment of interest, but their technology is far beyond the budgetary aims of our low-cost robot manipulator.

3.2 Trade-Off Analysis

Early in the design process, we knew it was pertinent to delve into the world of soft gripping end effectors. From past limitations and guidance from advisors, it became clear that a soft gripper was preferable for a sample collection system in a marine environment. At a high level, soft grippers (or underactuated grippers) have more degrees of freedom than actuation methods because the fingers continuously deform to the shape of the object [8]. For over 50 years, scientists have been experimenting with this end effector method and have classified all soft grippers into three categories, each denoted by their method of grasping. Two of these classifications grip by controlled stiffness and controlled adhesion, respectively. The final category, most important to this project, is grip by actuation. Actuation grippers consist of a wide range of technologies of varying complexity, including fluidic elastomer actuators, electroactive polymers, and shape memory materials [8]. However, the simplest actuation grippers consist of a passive structure with external motors. This application has the greatest compatibility with our robot manipulator due to the challenges posed and simplicity required in an underwater environment.

3.3 Design

Several different methods of providing the “softness” to a soft gripper are currently in practice on the market. All of these methods range from the material itself to force sensors on the gripper’s jaws that provide instant feedback. Grippers with flexible material are becoming more popular in robotics due to their simplicity and ease of manufacturability. 3-D printing the end effector with flexible material is much more simple and efficient than building a rigid end effector with force sensors. As such, the initial designs for this subsystem focus on grippers made with various flexible materials. Figure 3.1 below illustrates the group’s initial design for a gripper that opens and closes through simple linear actuation. Depending on the position of the vertical stroke, the flexible material opens and closes to either release or grip a marine sample.

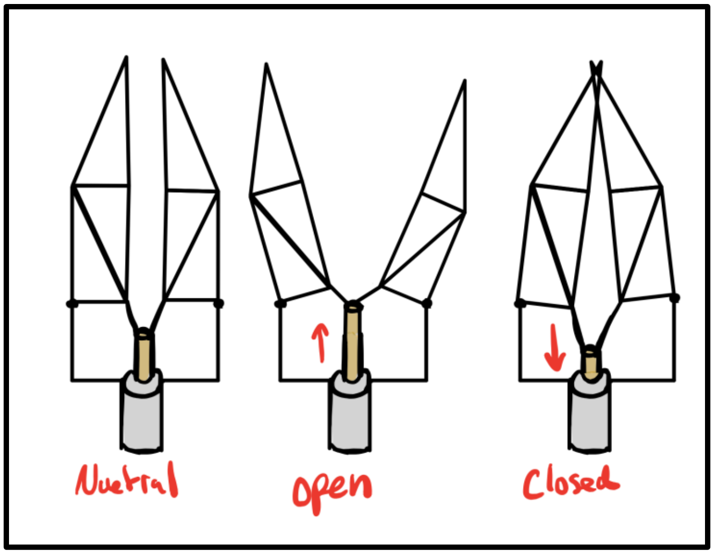


Figure 3.1: Principal concept of soft-gripping end effector

Now it is pertinent to investigate that method of actuation. The graphic above more closely resembles that of a linear actuator, something not within our budget. Underwater linear actuators, rated to our desired depth, cost thousands of dollars. Instead, we had to make use of an underwater servo, priced less than $500. Ultimately, to achieve linear actuation with the rotational capabilities of the servo motor, we employed a simple rack and pinion concept, seen in Figure 3.2.

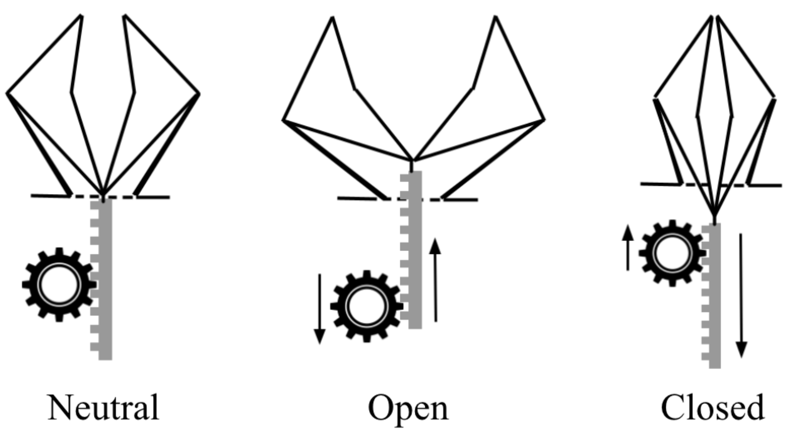


Figure 3.2: Mechanical concept diagram of gripper actuation

3.3.1 Prototyping

After completing initial research, our team immediately entered the prototyping phase, and began making simple designs from easily obtainable materials. These prototypes were extremely simple, only made up of two fingers instead of the four that would be used in the final design (Figure 3.3). Several were made from paper, while another used zip ties. The flexibility of these materials helped us understand how the design would flex around objects. This rapid prototyping gave the team vital insight into the mechanics of our design in an efficient manner.

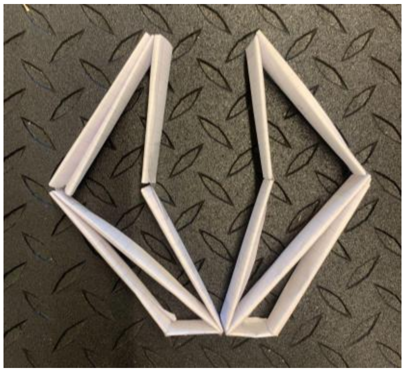


Figure 3.3: Two-dimensional rapid prototype

The next stage in our prototyping process was to create a larger, 3D prototype that had all four fingers instead of just two. This would allow us to actually test our ideas on a full scale and see if our chosen design would function as we had imagined. This prototype below (Figure 3.4), was made using balsa wood, scotch tape, hot glue, and construction paper. The balsa wood and scotch tape worked well as prototyping material, as it was sturdy, while still providing some flexibility, emulating the softness of our proposed gripper. This prototype also allowed us to test basic functionality using linear actuation to grab small items. These tests were successful in validating our principal design.

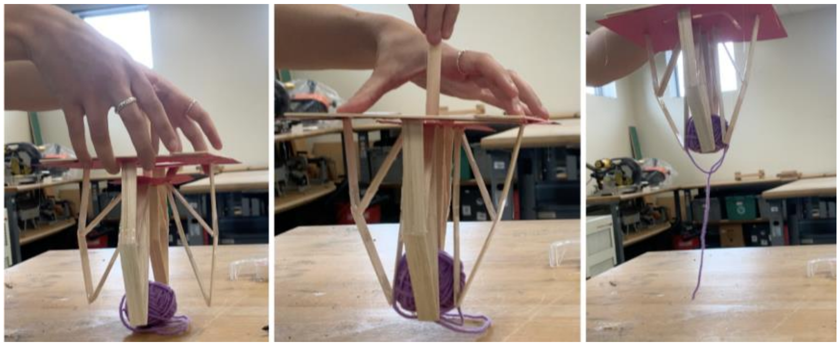


Figure 3.4: Balsa wood prototype demonstrating gripping process

After our balsa wood prototype confirmed our design functionality, we moved forward to prototyping with flexible materials. We purchased FILAFLEX 70A Soft TPU Flexible 3D Printing Material which was compatible with the standard Prusa printers available to us in the SCDI and Garage Maker Labs. The flexible filament posed several challenges when loaded onto the standard Prusa printer due to its unique characteristics. In order to load the filament, the printer's gears must be loosened with an Allen key such that the filament can reach the heated potion of the nozzle without bending and becoming tangled inside the nozzle housing. Once the filament is successfully loaded, printing can commence. Unfortunately, the quality of these prints was poor, marked layer thickness inconsistencies. The Prusa printers use filament that is pulled from a spool which results in smooth and uniform prints while using rigid materials. When our flexible filament attempts to turn its spool, however, the elastic material stretches before the spool spins over. This stretching causes the print layer to momentarily lose thickness before returning to the baseline. This process repeats itself during the print, resulting in a flexible 3D print wrought with inconsistencies and small separations between layers. Still, these flexible fingers, displayed in Figure 3.5, were fabricated well enough to perform critical prototyping and testing.

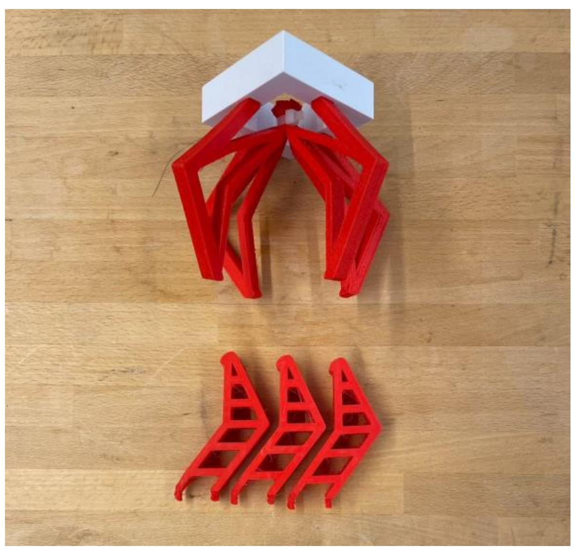


Figure 3.5: Flexible, 3-D printed fingers made with Prusa filament

Establishing 3-D print functionality with the Prusa flexible filament allowed for rapid fabrication of many gripper finger designs. Figure 3.5 displays two different finger designs, each printed congruently for direct comparison. Each was placed in a rigid, square housing and was actuated up and down with a human hand. Here, we quickly realized two issues. First, it was abundantly clear that this filament was far too soft. The fingers were far too flexible to grip any object. Second, we learned that printing the fingers separately was a recipe for fragility and inconsistency. No matter the material, securing the individual fingers to a rigid base would pose unnecessary challenges.

3.3.2 CAD Modeling

As such, we needed to iterate the gripper design to be printed entirely from a new, more rigid material. The entire gripper became a singular piece that attaches directly to the end effector servo housing. Figure 3.6 illustrates a four-fingered gripper that is both flush with the square base and that reaches a singular point in the center. The fingers are attached at that center, allowing that connection to be pushed up or down to open or close the fingers. Additional iterations resulted in thicker fingers and a thicker base, as highlighted in the final, manufactured design. Next, was the end effector servo housing itself. It needed to hold the servo, rack and pinion, buoyancy foam, and soft gripper, all in a compact, lightweight manner. Figure 3.7 displays this capability and proposed functionality. The rack runs along a notched column inside the housing, then attaches to the gripper's center point through an opening. The servo rotates an accompanying gear, thus opening and closing the gripper. Additionally, space exists to the left of the rack column, used to store the necessary buoyancy foam. Each CAD model was designed using Solidworks.

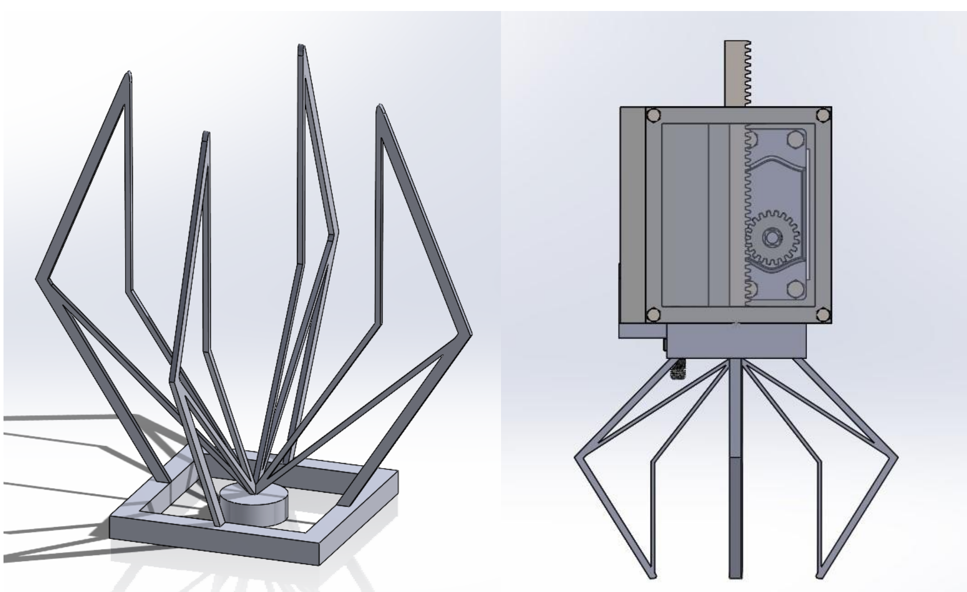


Figure 3.6: CAD model of end effector (left) and servo housing (right)

3.4 Manufacturing

As stated, manufacturing began using the Original Prusa i3 MK3S+ fused deposition modeling (FDM) 3D printers. PLA and TPU filament were used to print the rigid base and flexible fingers, respectively. Upon testing, it became apparent that the 55A hardness flexible TPU used by the Prusa printers was way too flexible. Here, the group shifted dramatically from FDM (Prusa) 3-D printing to stereolithography (SLA) 3-D printing. Using a Form 2 printer from Formlabs, this SLA method allowed the entire gripper to be printed with a flexible 80A hardness resin.

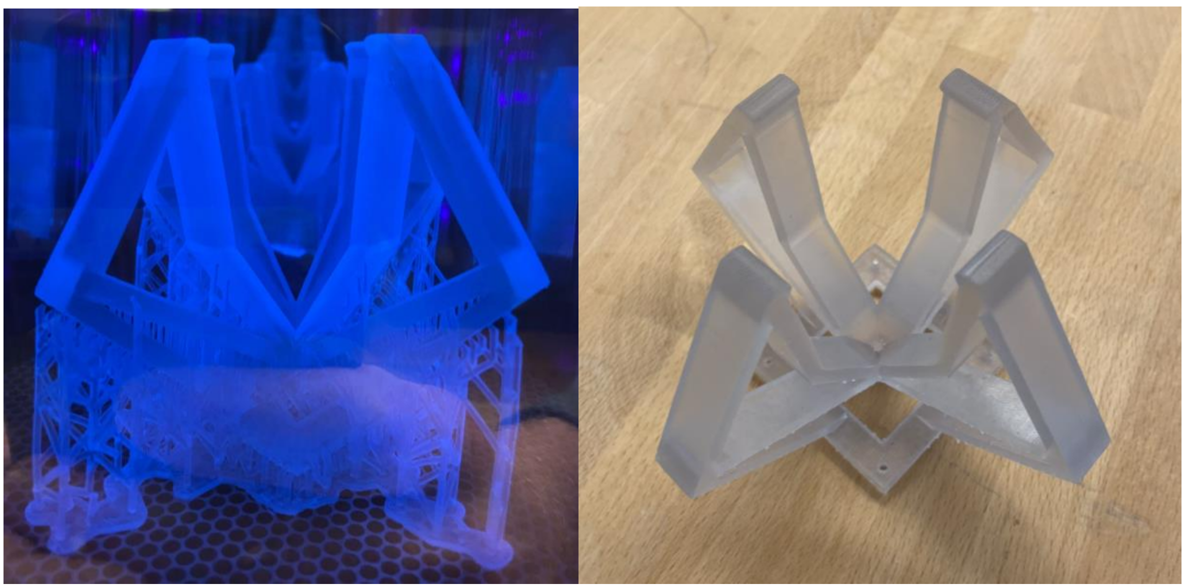


Figure 3.7: SLA curing process (left) and final soft gripper (right)

Figure 3.7 above shows the manufacturing process for the final end effector. Stereolithography uses illumination to solidify liquid resin one thin layer at a time. Upon completion, the object must undergo extensive post-processing. The print is doused in isopropyl alcohol and cured in a Form Cure for several minutes. Then, print supports were removed to achieve the finished product. With our soft-gripper completed, simple PLA prints using the Prusa printers were used for the rack, pinion, and servo housing. Finally, an additional door was designed to close the housing and to hold a laser pointer at the front of the end effector. The addition of this laser became useful for centering our end effector over the sample specimen of interest.

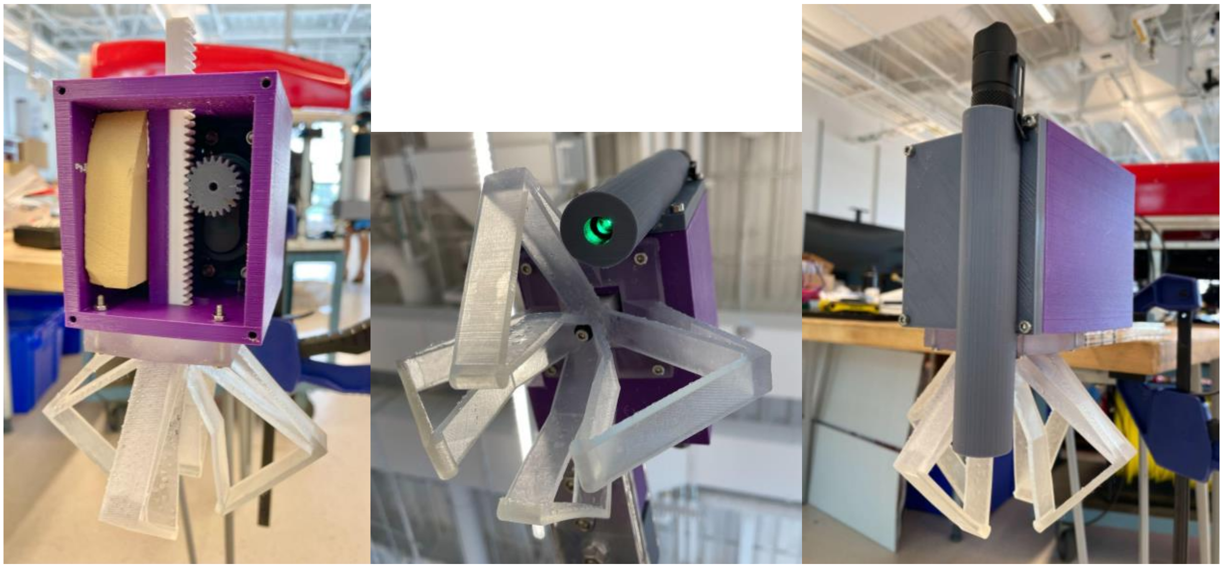


Figure 3.8: Final end effector fabrication

3.5 Challenges and Iterations

Our first main challenge occurred when the base of the gripper ripped. The base of the initial design was too thin and the attachment point for each finger was too small. This led to the break, which rendered the part unusable. As such, we printed and post processed a new gripper with a thicker base and larger finger attachment points. As circled in Figure 3.9, there is greater surface area where the finger attaches to the thicker base.

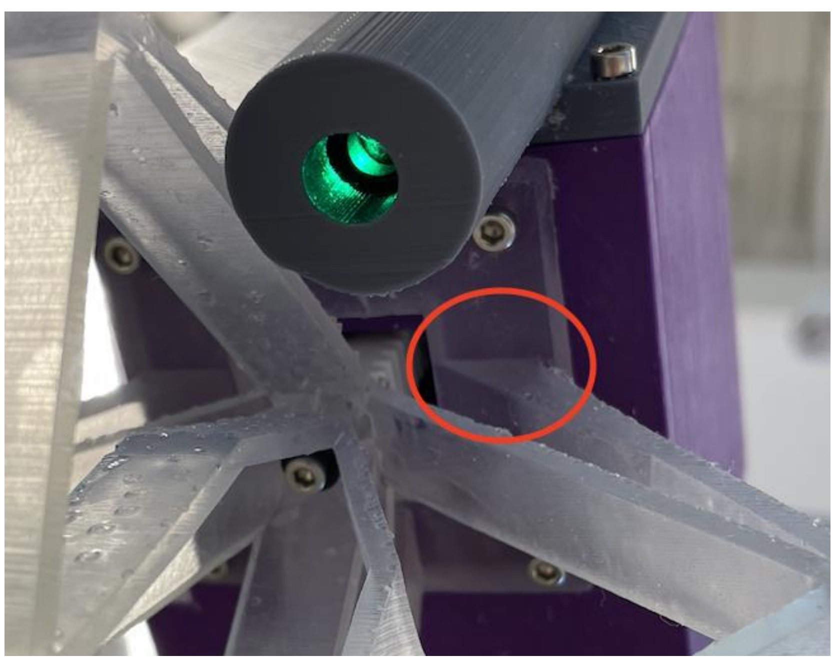


Figure 3.9: Highlight of thicker base and stronger connection point on soft gripper

Once the tearing problem was remedied, we also faced a problem properly securing the rack to the center of the soft gripper. Initially, the rack was printed with a pole to force through a hole in the gripper's center. It was then melted to prevent the rack from slipping out of the hole. When this proved insufficient, the rack was reprinted with its own 3mm hole, allowing for a screw to attach the gripper to the base of the rack. Although this required an extra washer to prevent the screw head from slipping through the soft gripper material, this method proved very effective and is employed in the final design. Ultimately, both manufacturing issues discussed here were easily resolved before the bulk of our testing.

3.6 Final Milestones

Once the gripper was fully manufactured, it was partially assembled so the servo could be attached and functionality could be tested. The rack was printed slightly larger than the slot built into the housing so it had to be sanded down before it could all be assembled for the first time. However, once all the parts were fit together, the gripper was able to open and close using the rack and pinion as actuation from the servo, a major success. After this, more milestones like integration with the arm and actuating underwater and successfully gripping something underwater were achieved. During this phase, the gripper was also put through a cycle test, where it was left to cycle through the open and closed position around 500 times. This test showed the durability and longevity of the design and validated the material choices we had made. The last large milestone was the installation of the underwater laser pointer. This greatly improved process of centering over an item, making it easier to grab items.

Section 4: Robot Arm

4.1 Trade-Off Analysis

Multiple different possibilities for an underwater manipulator system exist, and the main focus of the design stage was to narrow down the scope into an arm that was both cost effective and achievable within the school year. The arm would have to be able to move across the desired workspace while also being within the field of view of the camera attached within Nautilus. The arm would also need to be sturdy enough to lift its own weight underwater as well as the weight of the samples that will be placed in a storage system. Lessons learned from the previous year's robot arm design led to focus on the stability of the arm structure as well as improving the functionality of the end effector.

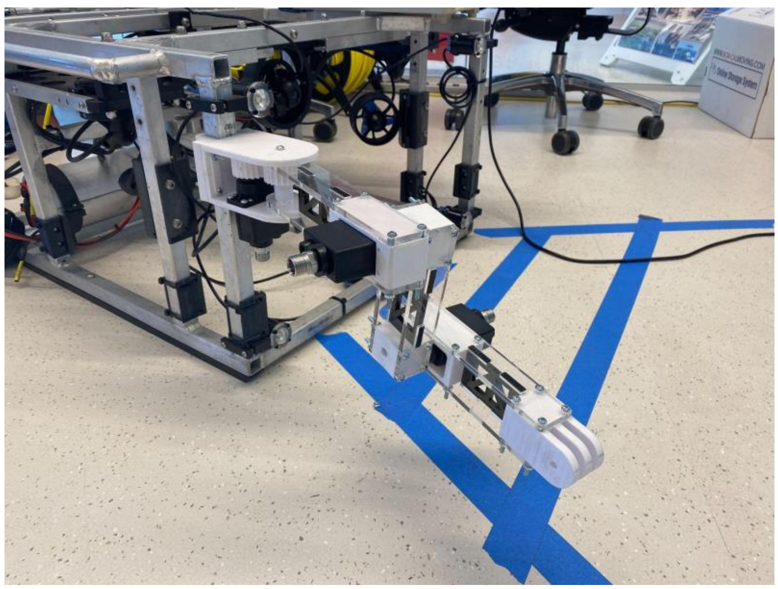


Figure 4.1: Previous robot arm design

When we considered the previous year's designs, a three revolute joint serial chain manipulator, it was determined that the design would not be sufficient for the performance that was desired. One of the concerns from the previous design was that the end effector was in a fixed orientation with respect to the last link. As a result, the user was required to position the end effector at the right position as well as find the correct orientation in order to grab the sample. Additionally, we wanted the system to be more rigid while moving in the water. To address these changes, we decided to design a system where we can keep the end effector in a fixed orientation during deployments while also improving the overall stability of the system.

4.2 Design

The design of the arm required a minimum of three degrees of freedom in order to allow for enough movement in the x, y, and z directions to grasp the object of interest. The previous year's team had implemented three underwater servos for their arm design, and our team decided to keep the same number of servos and create a three degrees of freedom arm as well. Furthermore, the workspace had to be defined before considering new configurations for the arm, which was derived from the area of the seafloor that would be visible to Nautilus' forward facing camera. The robot arm also had to be capable of reaching the sample storage system located at the bottom frame of Nautilus.

Our team explored ideas outside of serial-chain manipulators and concluded that the use of a parallel linkage would be worth exploring. The parallel structure provided two of the three needed degrees of freedom, as well as gave extra support to the links in the system. In addition, the design allowed the final link that was attached to the bottom corner of the parallel structure to remain horizontal throughout the entire range of motion of the arm during operations. Because of the chosen design, the end effector that was attached to the last link remained in the same orientation which eliminated the need for an extra servo to act as a wrist. Figure 4.2 shows our initial design of the arm while Figure 4.3 displays the arm attached to the front of Nautilus.

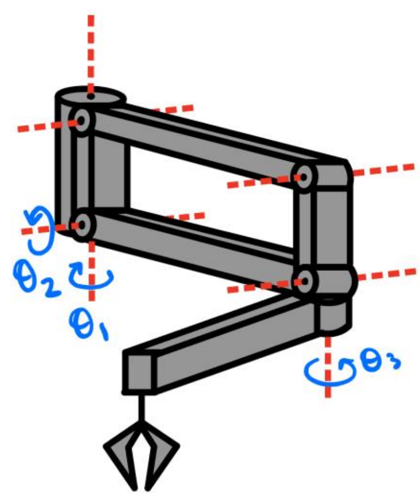


Figure 4.2: Initial Nautilus arm design

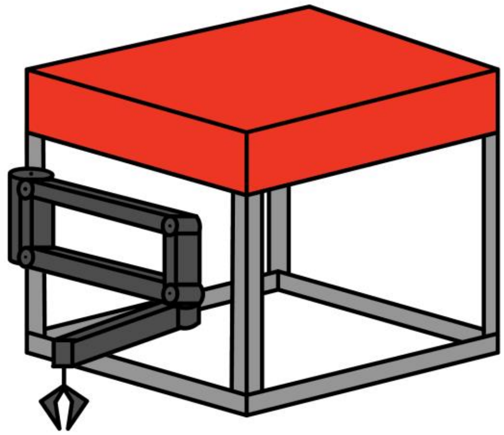


Figure 4.3: Initial arm design on Nautilus frame

4.2.1 Prototyping

After discussing possible designs, prototyping was done to validate initial decisions. The first prototype consisted of a miniature version of the arm shown in Figure 4.4, which included a 1/4th scale Nautilus, arm, and workspace. The prototype gave the team a rough idea of how the arm would look as well as how it operated in a certain workspace.

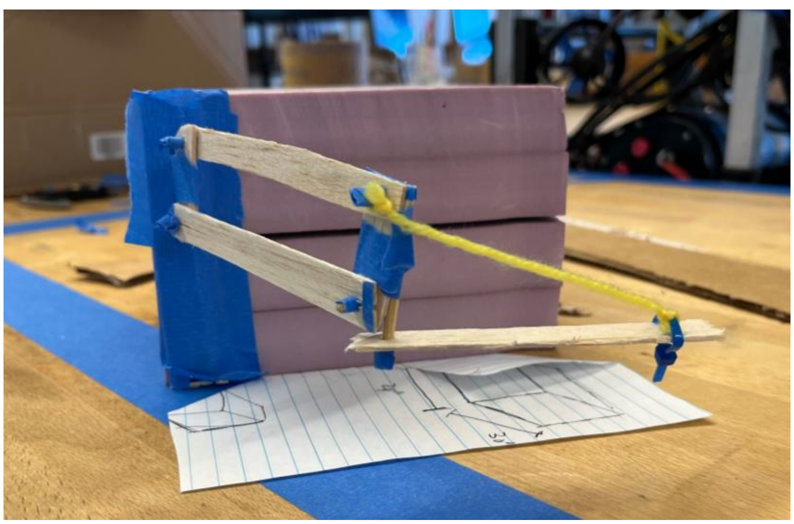


Figure 4.4: First arm prototype, miniature version

Afterwards, the design was prototyped full scale with balsa wood and zip-ties to make the revolute joints, which can be seen in Figure 4.5. It was necessary to create a full scale prototype on Nautilus to ensure that the arm in home position would not block the camera attached to

Nautilus. As a result, the design of the parallel structure was relatively large so that the camera could see through the empty space between the links of the robot arm. The second prototype also allowed the team to finalize dimensions for the links of the arm as well as the workspace.

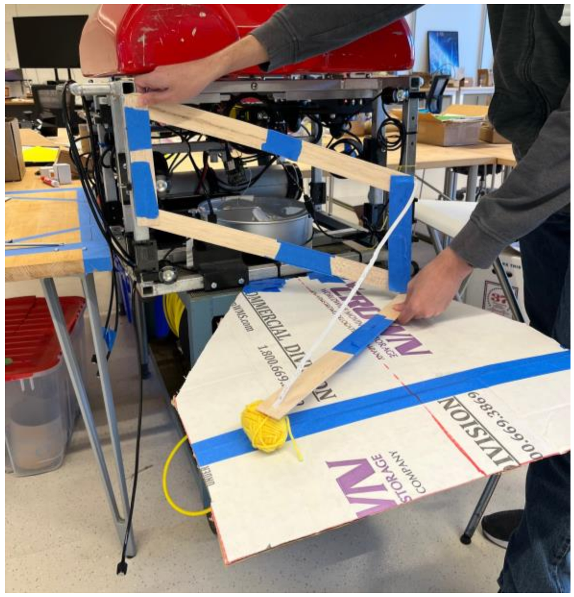


Figure 4.5: Second arm prototype with Nautilus

4.2.2 CAD Modeling

After using the prototypes to nail down the dimensions of the arm as well as the workspace, we began the design and modeling process on SolidWorks. The biggest challenge we had to face was figuring out how each joint would be actuated while also placing the servos in the most optimized positions. Due to the size of the system, the team wanted to avoid direct actuation and opted for a 1 to 1.6 gear ratio. The torque output from the servos was increased without decreasing the range of motion from the servos greatly. Another point that was taken into consideration for the design was the potential to add another servo at the upper corner of the parallel structure on the side that is connected to Nautilus' frame. The initial CAD model of the arm along with an early CAD model of the end effector is shown in Figure 4.6. The transparent vertical bar towards the left of the figure represents a part of the Nautilus frame. While not shown in our CAD models, the horizontal sections of the parallel structure were designed to have pieces of buoyancy foam epoxied in the empty spaces between the acrylic plates of the arm.

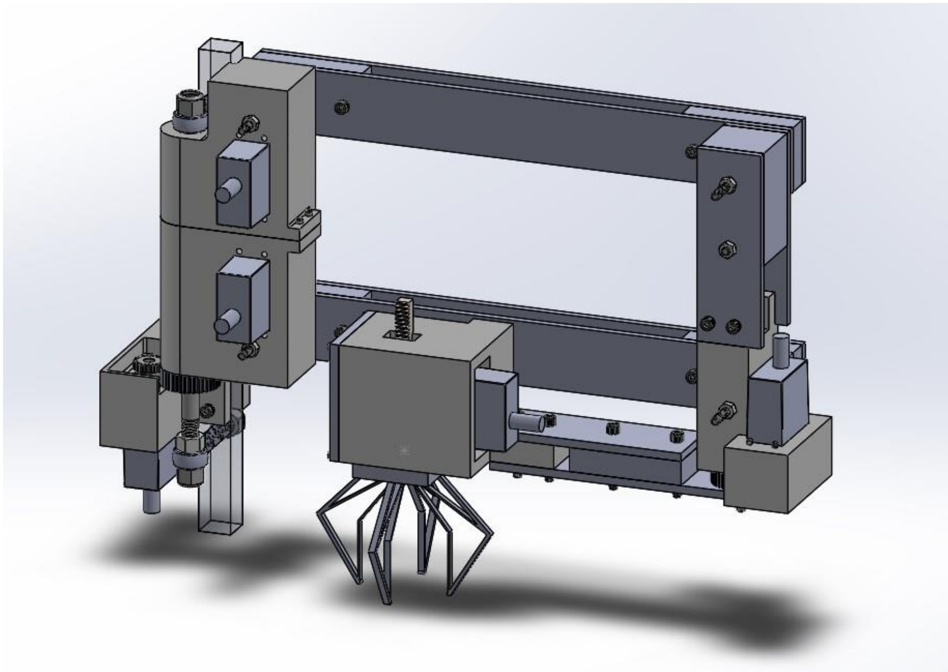


Figure 4.6: CAD model of initial arm design

While the design was meant to optimize the performance of the soft gripper, the team wanted room for modularity as well. As a result, the team also designed a fork-like end effector that would be able to pick up instruments with a “T” bar (Figure 4.7) in order to prove that the robot arm could have various kinds of end effectors attached.

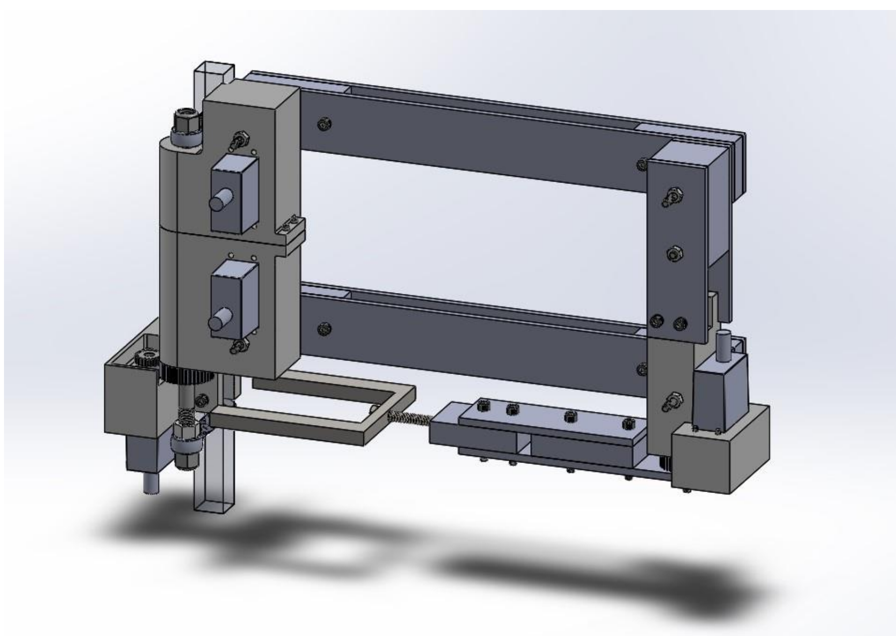


Figure 4.7: Initial arm design with fork end effector for “T” bars

The design went through multiple iterations during the entire manufacturing process. The major changes from the initial design included removing the upper servo from the parallel structure, which was mainly meant as a placeholder for future design iterations, adding a collar to the main connecting rod that's attached to the frame, and reinforcing the strength of the last link to ensure that it can hold the weight of the end effector. Our team's final CAD model of the arm with the soft gripper end effector is shown in Figure 4.8.

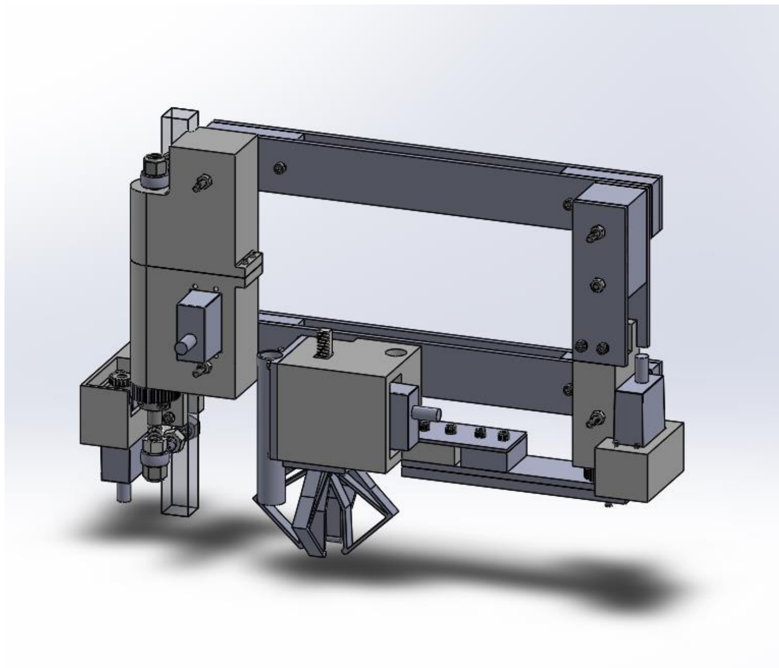


Figure 4.8: Final arm design

4.3 Manufacturing

The arm consisted of 3D-printed parts, laser cut-acrylic, and small parts ordered from McMaster Carr. For 3D printed parts, the team used Prusa printers available at the school facilities. In order to maximize efficiency with limited time available, a low infill was chosen, and both PLA or PETG filament was used for the material based on availability. A 30-40% infill was used on the 3D printed parts to minimize print time yet still provide the durability needed for the arm. A lower infill also reduced weight in the overall system. Overall, these decisions allowed for more prints and prototyped parts for the robotic arm in a shorter amount of time. For the parts of the arm that required acrylic, epilog laser cutters were used to cut 1/4 in. acrylic sheets. The design required 1/2 in. acrylic sheets which were not available in the Maker Lab. As a result, two glued acrylic sheets were used as a placeholder. After the first few prototypes were complete, the team added buoyancy foam within any empty spaces found in the robot arm. The buoyancy foam was cut using the bandsaw in the machine lab and epoxied to acrylic sections of the robot arm.

4.4 Challenges and Iterations

This section addresses the design choices our team made through our multiple iterations of our arm design that led to our final prototype. As mentioned in section 4.3, our team made manufacturing decisions in order to maximize our efficiency. Due to the availability of the Prusa printers and the numerous parts needed to be printed, 3D printed parts of the arm were a mixture of PLA and PETG. These parts led to uncertainty of the buoyancy of our system. We addressed this issue by placing buoyancy foam in the arm and later tested the overall buoyancy of the arm with Nautilus in the garage test pool. Something the team noticed during initial ballasting tests was that water was seeping into some of the larger 3D prints. This however didn't lead to any major issues with buoyancy because the arm was attached to Nautilus, but we are aware that this might pose an issue for long term use.

One of the early design concerns we had was how the arm would hold its weight when it's not in water. The first issue that we addressed was holding the arm in place as users are working with Nautilus. Without the buoyant forces it would've been difficult to hold the arm in its home position when out of water. For the parallel structure, it would've been impossible for our servo to keep the arm upright because the torque due to the weight of the arm alone would overpower the servo and potentially damage it. It would've also required that the servos be powered the entire time Nautilus was out of water which was not an optimal solution from an energy efficiency perspective. To remedy this issue our team decided to create a sling that used the parallel design of the arm to our advantage to hold the system in place. The sling would be easily taken off once Nautilus is in the water and ready to collect samples. The initial design for the last link was originally too weak to hold the end effector's weight in air. Our final iteration reinforced the link with extra pieces of acrylic. While it wasn't the most optimal design change, it was sufficient for us to use during testing. Another change for future designs that we discussed was creating a cable attachment from the parallel structure to the end of the last link which would add extra support.

During the deployment to MBARI, an unexpected challenge occurred when Nautilus with the robot arm attached was put into the water. As Nautilus was diving down to the bottom of the test tank, the rapid changes of direction of the ROV forced the robot arm to be jostled around and changed the home position of the joints controlling the motion of the robot arm. Specifically, the gears on each of the joints, which is shown in Figures 4.9-4.11, slipped out of position. In order for the robot arm to function properly, and due to the limited range of motion of the servos, the gears need to be positioned correctly at the home position in order for the links of the robot arm to move at its desired range. However, the gear slippage reduced the full range of the robot arm.

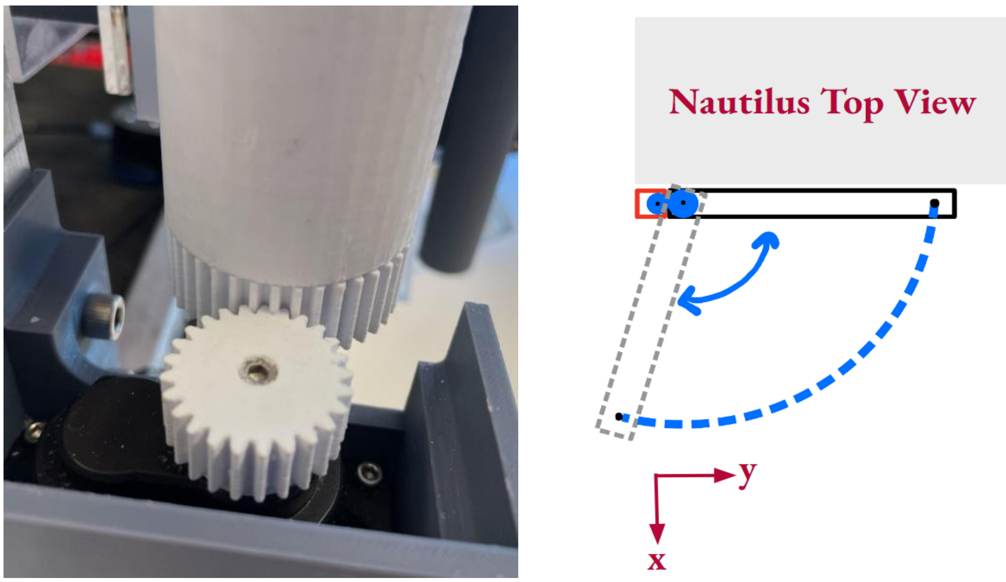


Figure 4.9: Joint 1 gear connection (left) and range of motion (right)

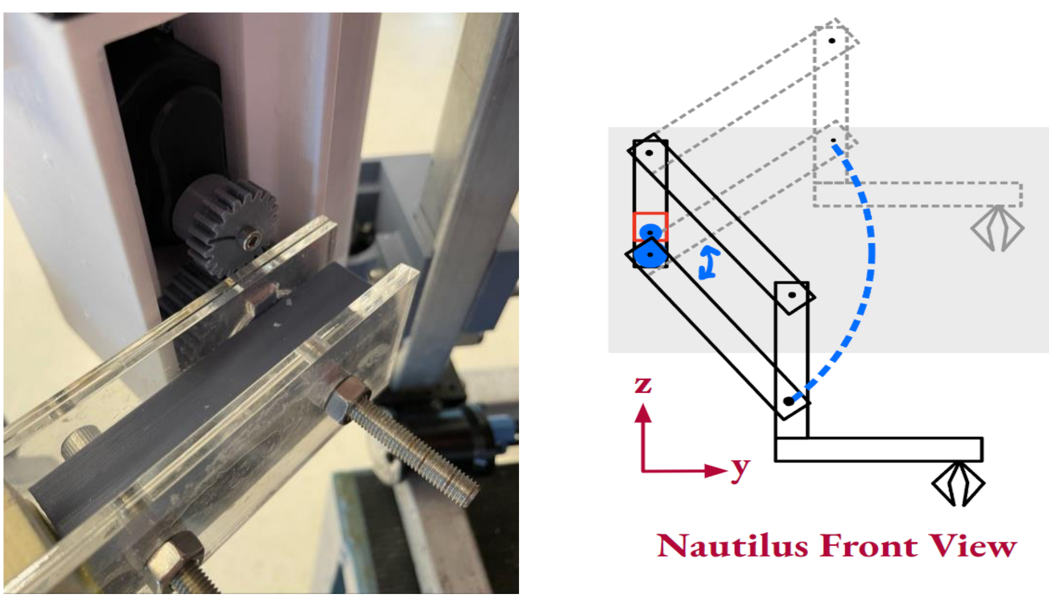


Figure 4.10: Joint 2 gear connection (left) and range of motion (right)

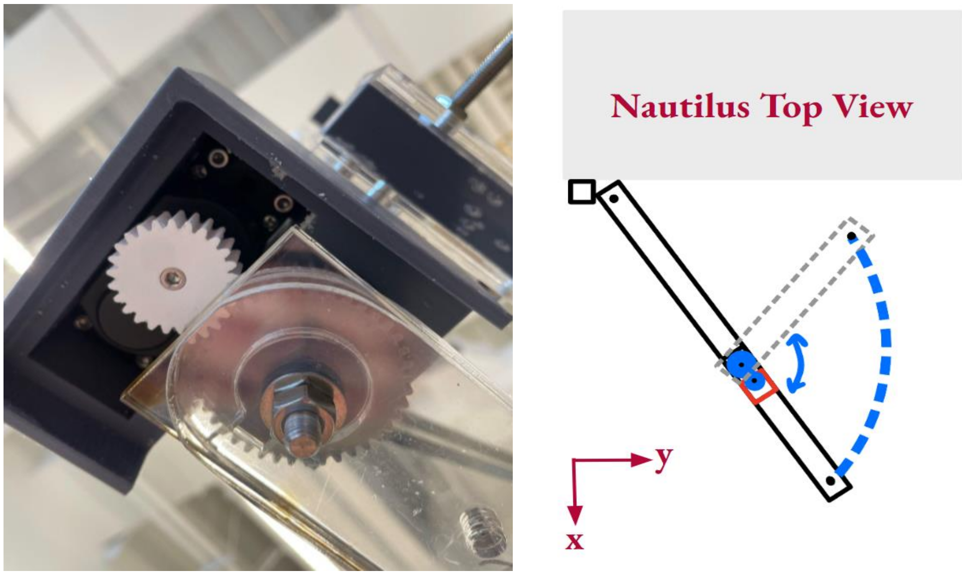


Figure 4.11: Joint 3 gear connection (left) and range of motion (right)

As a result, members of the team had to move the gears back into home position after having Nautilus return back to the surface (Figure 4.12). After removing the screws holding the gears and returning everything to its original positions, the deployment was continued, but Nautilus had to be maneuvered slowly to minimize the water pushing against the robot arm, which would cause additional gear slippage. This was something we were not able to address during the scope of our project; however, we were still able to continue with other tests on the arm in our smaller test pool in a more controlled environment that minimized gear slippage.

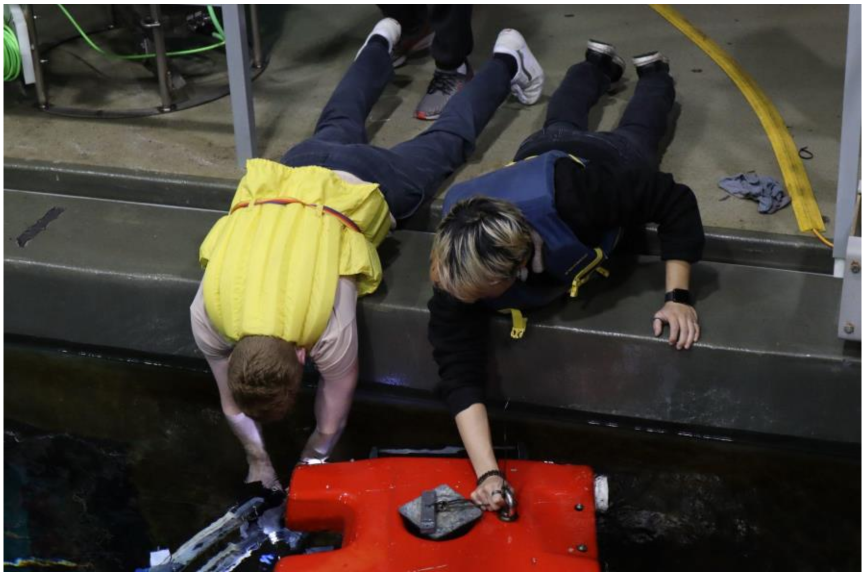


Figure 4.12: Fixing the gears during MBARI deployment

4.5 Final Milestones

Once the arm was manufactured, iterations on the design were made to both reinforce the structure and ensure clearance for arm movement. The arm was also integrated with the gripper, which consisted of a rack and pinion, as well as its housing that was designed to interface with the final arm link. This arm link was designed with modularity in mind which would allow for easy swapping to future end effectors. The final manufactured prototype of the robot arm is shown in Figure 4.13. This showcases the entire robot arm attached to the Nautilus ROV.

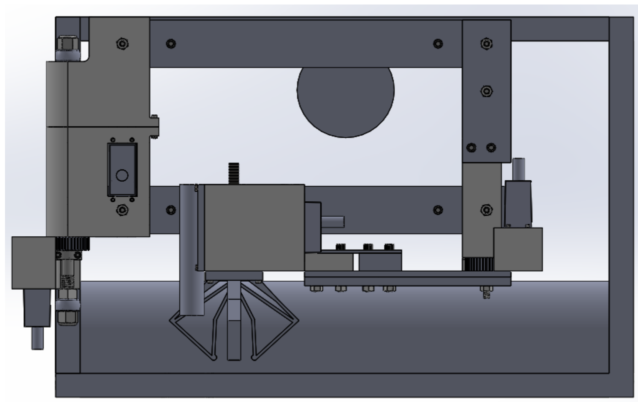


Figure 4.13: Final arm design on Nautilus

While there were some issues that still need to be addressed in future iterations, the final arm (Figure 4.14) was able to successfully operate in water to collect samples. Because the last link was able to remain horizontal, the end effector was always in the optimal orientation to grab each sample and drop them into our storage system within the view of the camera. It was also able to support its own weight out of water with the help of a sling and remain neutrally buoyant with the added buoyancy foam.

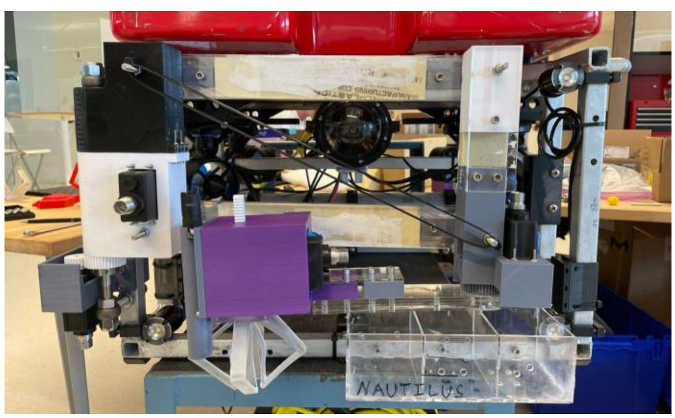


Figure 4.14: Final manufactured prototype

Section 5: Storage System

While a smaller, much simpler subsystem, the storage compartment is just as critical as any other. The rest of the sample retrieval system is rendered useless without a place to properly separate and store various marine samples. Due to limited camera view, several questions and challenges arise when deciding on a storage design. One thing that *must* be avoided is a blind drop. The storage system must be at least partially in view of the camera to avoid blindly dropping the specimen into the storage compartment.

5.1 Design

There were two schools of thought when designing a storage system that met our requirements. First, was to construct a motorized drawer that moves from inside Nautilus out into the field of view of the camera. The other, more efficient solution was to attach a static container to the side of Nautilus that was always within the camera's view. Both options were considered, but in this subsystem, less is more. Seen near the bottom of Figure 5.1, we went forward with a static storage system that is attached to the front right side of the ROV. It is within the arm's workspace and the field of view of the camera.

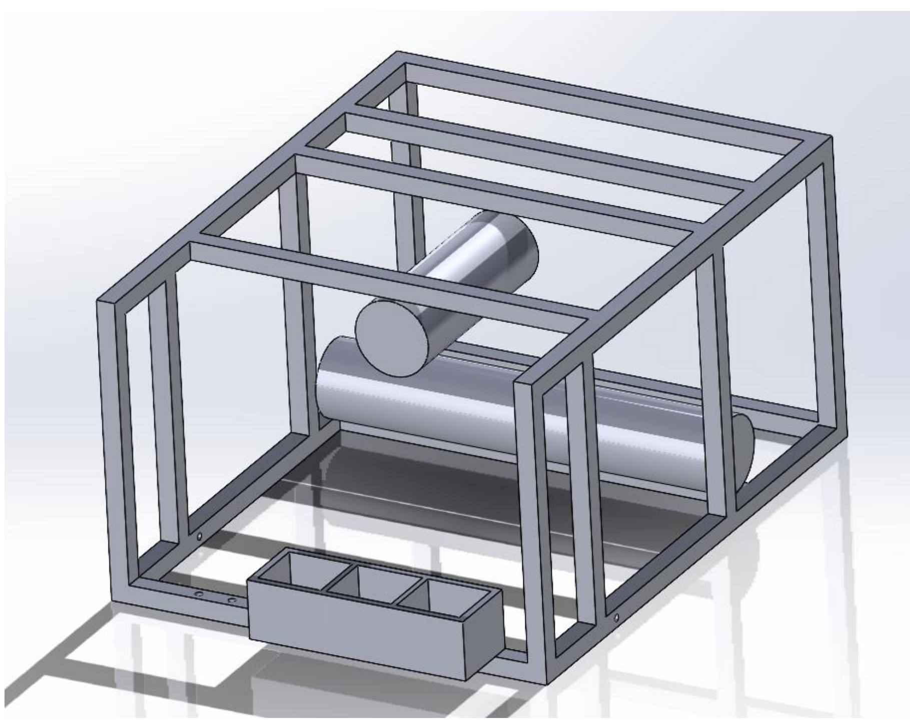


Figure 5.1: CAD assembly of proposed storage design on the Nautilus ROV frame

5.2 Manufacturing

While the initial concept was intended to be 3-D printed, Figure 5.2 highlights the final, functional design of the storage system. Laser cut acrylic was glued together to form a box with 3 separate compartments. Although a clamp design was considered to attach the system, ¼ inch holes were drilled into Nautilus' frame to ensure durability of the connection. Again, this simple design works flawlessly. Requiring no complicated movement, the storage is within the view of the camera and within the workspace of the arm, all without intruding on the arm's operable space. The middle dividers are removable, making the storage system adaptable to different size samples and organization strategies.

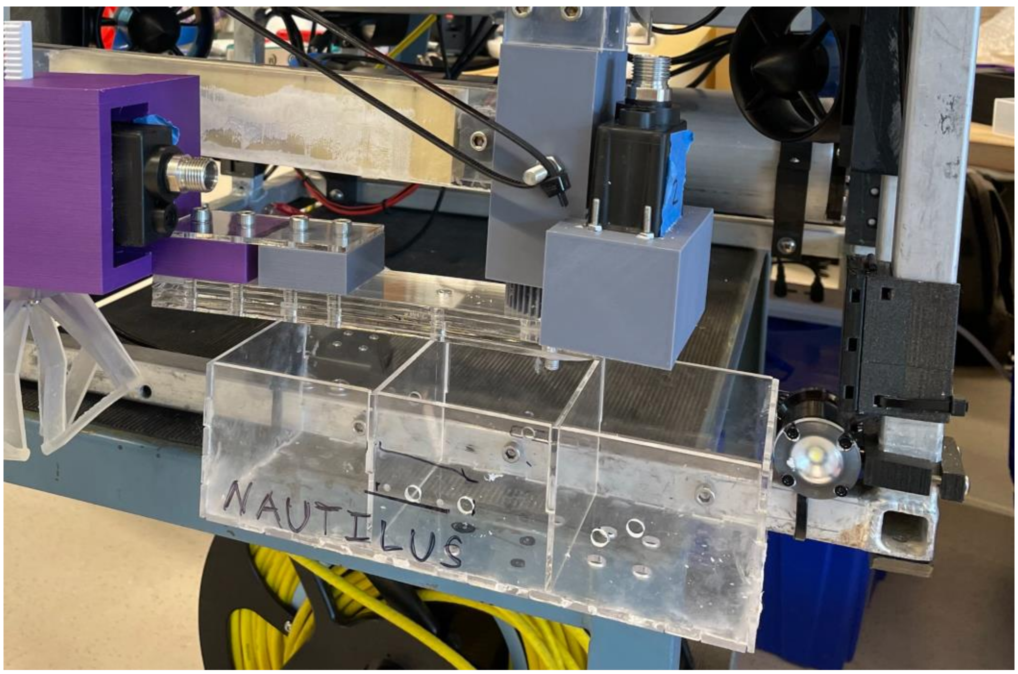


Figure 5.2: Final manufactured storage system

Section 6: Computing

6.1 Electronics Overview

As seen in Figure 6.1, the electronics for Nautilus were split into three main subsystems: the laptop, main control system, and arm control system. Our team received a laptop upgrade midway through the year, and so we used a new Dell Latitude 5430 Rugged during all of our tests. This laptop was able to efficiently and effectively run all of the code, with the majority of the delay coming from transport over the tether. The main control system was responsible for the movement of Nautilus's frame, such as thrusting forward or rotating clockwise. The arm control system was responsible for moving the individual arm servos, providing precise joint control as our team worked our way towards endpoint control. Both the main control and arm control systems were piloted using Xbox controllers, which were connected through the laptop. While using two separate controllers also meant that we had to have two operators during testing, it allowed for greater control and dexterity of the arm's joints with access to two joysticks on the arm's controller.

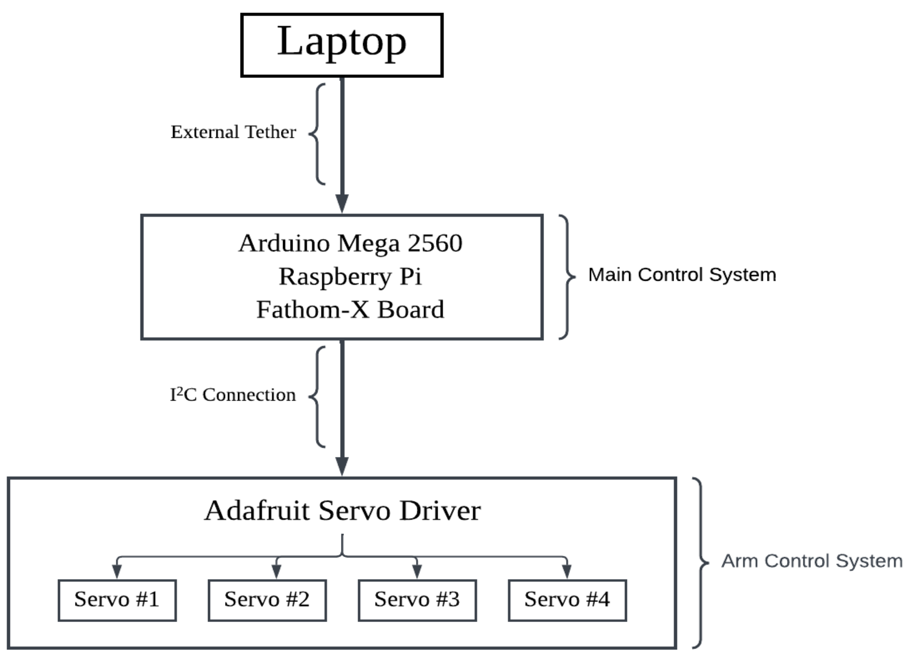


Figure 6.1: Electronic overview diagram

Waterproof tubes were used to hold the two control systems, with a third holding the batteries that powered the main control system as seen in Figure 6.2. This battery tube could hold up to three 14.8V LiPo batteries. In an effort to consolidate the arm tube so that we did not have to make any more physical additions to the ROV, the arm's battery was kept within its own tube and did not have a separate battery tube. This decision was feasible because the arm control system did not require as much power as the main control system. While we never encountered any major leaks within these tubes, our team had to replace some of the connectors since the epoxy was wearing off. These new black connectors can be seen among their older red counterparts in Figure 6.3.

Figure 6.2: Waterproof battery tube

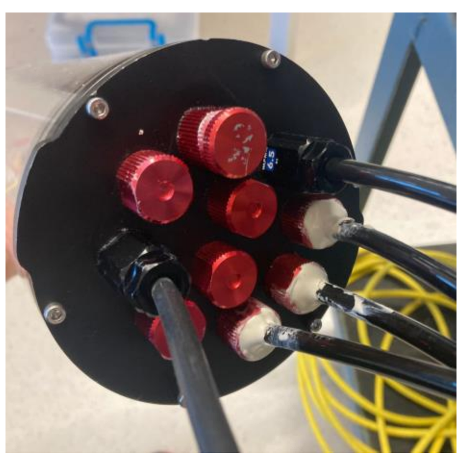


Figure 6.3: Waterproof tube with improved connectors

6.1.1 Main Control System

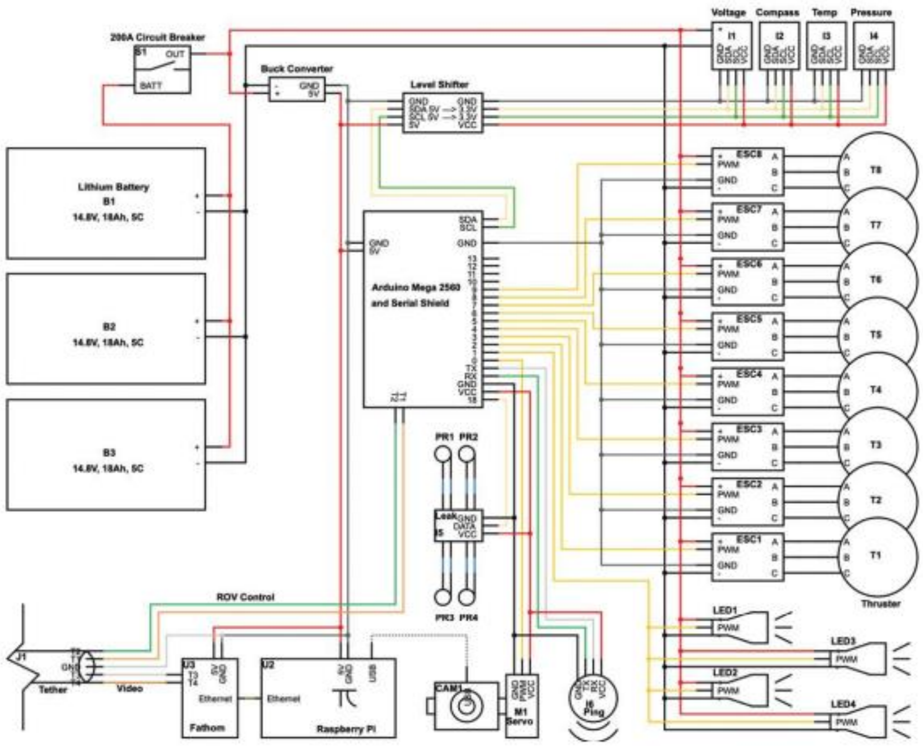


Figure 6.4: Previous year’s electronic wiring diagram [9]

As mentioned in the previous section, the main control system was responsible for the movement of Nautilus, as well as things such as switching its lights on and off and reading sensors. This system handled everything that did not have to do with the arm, with all of its components pictured above in Figure 6.4. Our team inherited this system from previous years, and there was no need to change the design layout or add additional parts because Nautilus moved and worked satisfactory before our project. Since our main focus was on the arm, we decided that any significant changes to this control system would be a misallocation of time and effort.

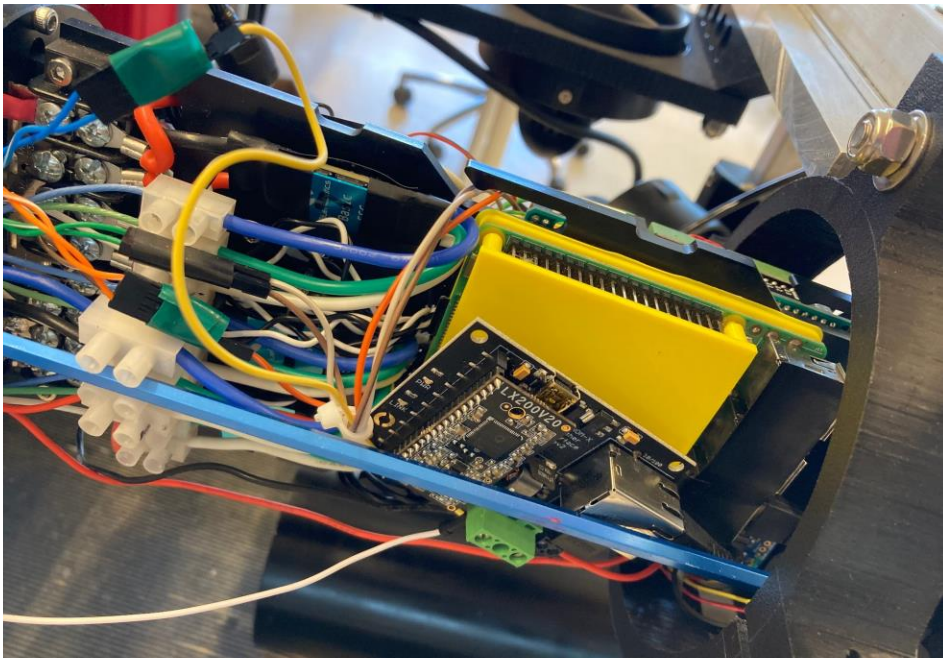


Figure 6.5: Main control system tube

The three principal control components within the system were an Arduino Mega 2560, a Raspberry Pi with Fathom X board, and Blue Robotics electronic speed controllers (ESC) for the thrusters. The Arduino was responsible for communicating with the laptop via tether, and forwarding packets to the correct motors and boards. It also sent back data gathered from sensors placed along Nautilus. The Arduino did not have to run any calculations, making the system much more efficient. The Raspberry Pi was connected by way of the tether via ethernet through the Fathom X board, and was responsible for video and image capture. Camera delay was a problem during our team's tests, but it was outside of the scope of our project to tackle. The ESCs were used to communicate between the Arduino and thrusters, ensuring that Nautilus changed direction in controlled and measured movements. These control components were all seamlessly integrated into a singular waterproof tube, as seen in Figure 6.5.

6.1.2 Arm Control System

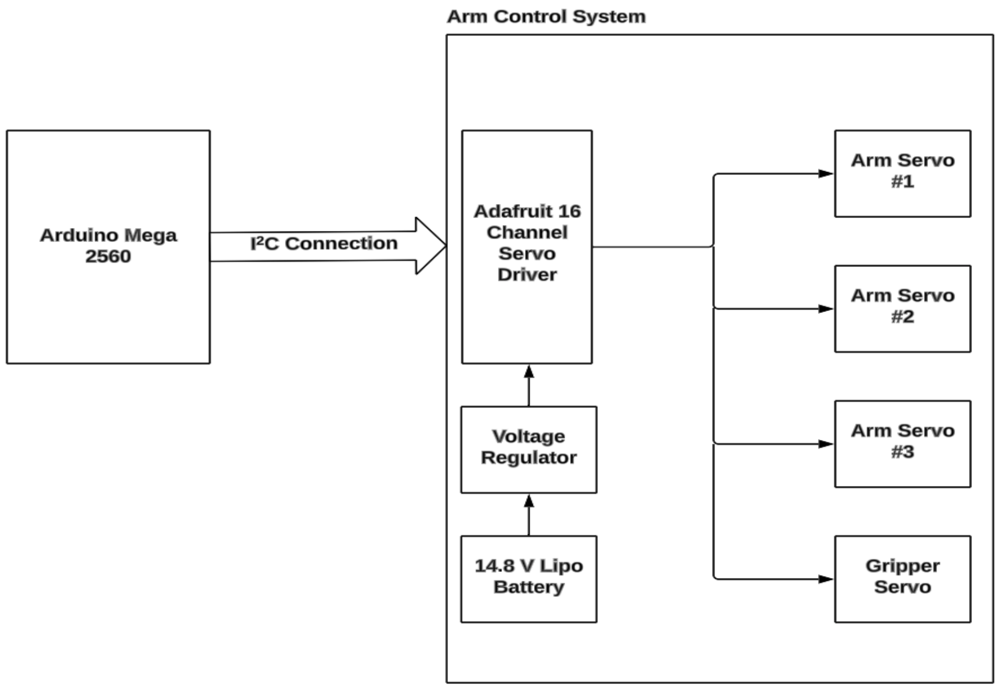


Figure 6.6: Arm control system diagram

The arm control system, whose components are pictured in Figure 6.6 and were also inherited, was solely responsible for the movement of the four arm servos. An Adafruit 16 channel servo driver was used to receive signals from the main Arduino and forward them to the correct servo. This transfer of signals was done using an I^2C connection. Over the short distance between waterproof tubes, there was not much delay or packet loss, so it was a viable option. It also meant that the arm servos did not have to be directly connected to the Arduino, whose ports were already crowded. Ultimately, our team decided to keep this layout because it provided useful modularity when working with the electronics. If something with the arm was not working properly, we did not have to also dive into the main control system tube to check if there was a problem. This kept our team's system isolated and easy to work with and update as we saw fit.

Figure 6.7: DPC-11 servo programmers

Servo programmers were also an important piece of hardware utilized by our team that was not attached to Nautilus. These programmers, seen above in Figure 6.7, allowed us to reprogram the arm servos to have an increased range of motion. The range was improved from 70 degrees to 130 degrees of freedom. Updating the range meant that Nautilus's workspace was increased, so picking up objects was much easier. The servos only need to be reprogrammed once, so future years should not have to worry about reprogramming them unless they add or replace servos.

6.2 Software Overview

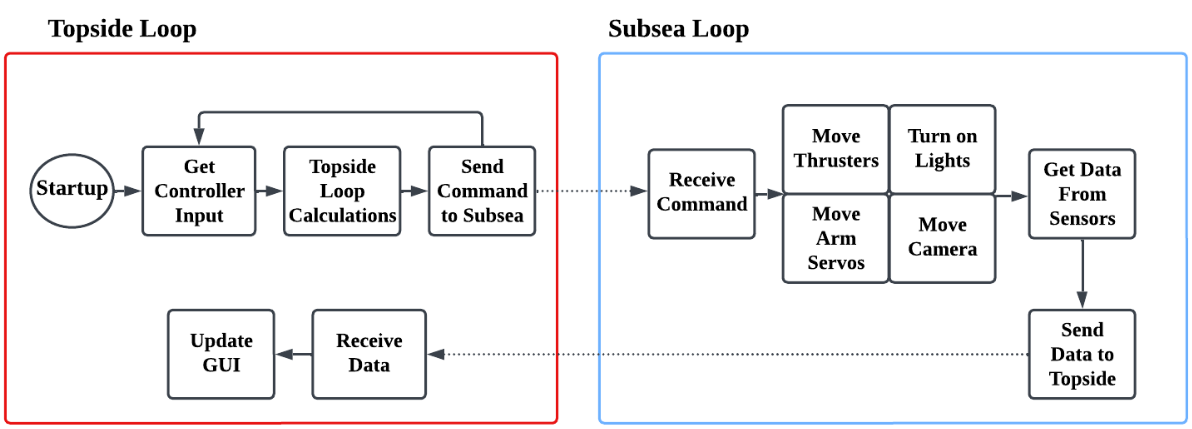


Figure 6.8: Software overview flowchart

The software was split into two loops, a topside loop and a subsea loop, as seen in Figure 6.8. The topside loop was run on the Dell laptop discussed in the electronics section, and was written entirely in Python. All angle calculations were performed within this loop after the controller input was obtained, and values were formatted as a NMEA (National Marine Electronic Association) string. The string was composed of different tokens, which were just comma separated values. This format made it easy to send servo angle values for each link of our arm. These strings also meant that there was a consistent configuration that the Arduino always received, so parsing the strings was the same process every time. This procedure made communication between the laptop and Nautilus uniform and efficient.

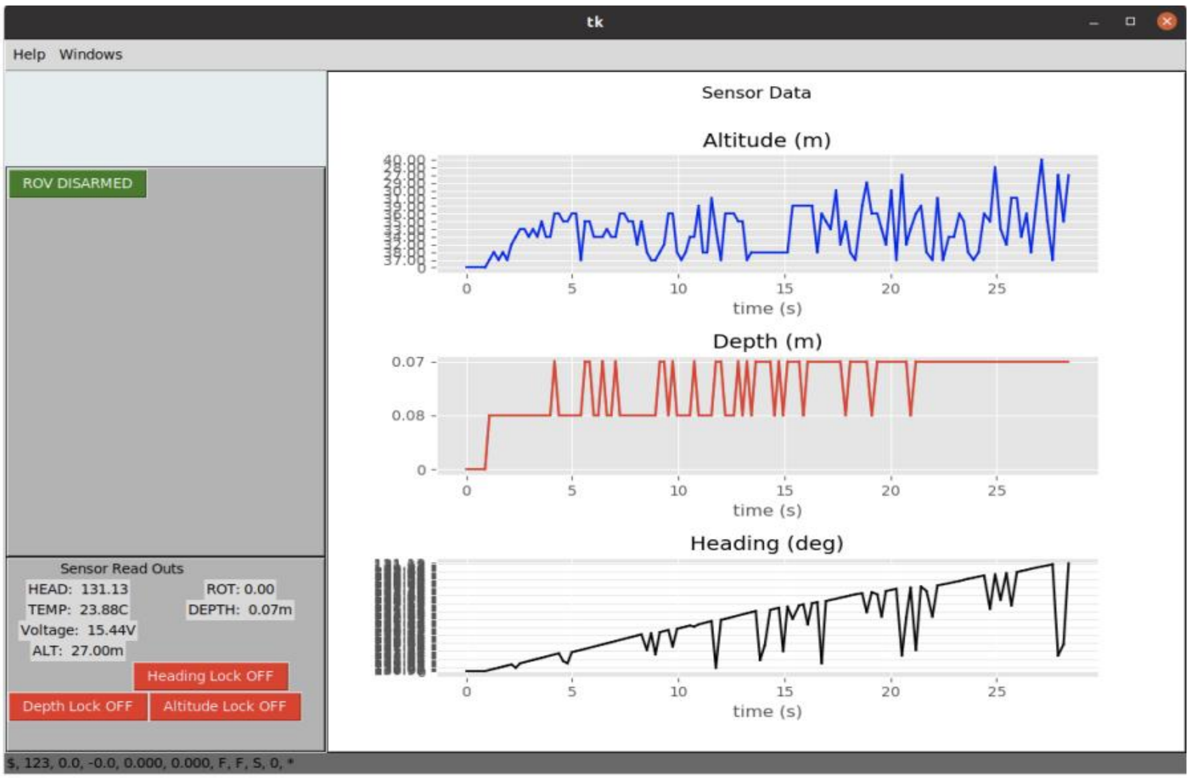


Figure 6.9: Nautilus graphical user interface

The subsea loop was written entirely in C and ran on the Arduino Mega 2560. Once a command was received by Nautilus through the tether, it forwarded the values from the NMEA string to the corresponding motors, sensors, and thrusters. Once all appropriate actions had been taken, data was read from Nautilus's various sensors and sent back to the topside laptop. These sensor values were then displayed on the GUI, as seen in Figure 6.9. Extremely useful for operating Nautilus safely and securely, this GUI is what operators relied on to alert them of any problems with the ROV. For example, during one of our tests, our team realized that our battery was running too low because of the reading from the voltage sensor. The camera feed is also displayed through the GUI, making Nautilus almost inoperable without it.

6.3 Software Challenges and Iterations

Since our team also inherited the code base from previous years, the majority of software problems we faced involved implementing our Cartesian end point control. Our initial trials with this method involved running calculations on a test Arduino. However, we quickly realized that the calculations ran too slowly, and we would have had to add delays to synchronize the actual servo position and the calculated arm position. These added delays would defeat the whole purpose of running other calculations on the topside laptop. The values that we produced using this early code were also slightly off, with its error compounding as the simulation went on. To remedy these problems, our team shifted our focus to producing code that would create exact values without having to use the Arduino for any calculations.

Our first attempt at a solution was to send values directly from Simulink over a serial port to the Arduino. The challenge with this method was that the Arduino can only have one serial port connection at a time, and so the serial port that transferred data between the laptop and the Arduino no longer functioned, making Nautilus useless. Another solution that we tried was generating Python code directly from the Simulink model. However, after extensive research, we could not figure out a way to effectively implement this method with our system. Finally, we settled on writing our own Python script from scratch. We were able to use pieces from our initial test Arduino C code, supplementing it with Python libraries to make the values more accurate and usable. Implementing the code in this fashion eliminated the synchronization problem seen with the initial Arduino code. This method eventually worked, and we were able to see encouraging results within the test pool.

6.4 Final Software Milestones

Both of our biggest software milestones involved the control of the arm. Our team was able to successfully implement joint control without any software bugs or hindrances. It was also easy to reconfigure the starting angles for a given need. As stated before, we also got a preliminary version of cartesian end point to work. While it was not fully functional, the code that we implemented can be easily built upon so that it can become fully functional in the future.

6.5 Controls

The goal of the controls portion of the system was to create a velocity Cartesian endpoint control scheme to allow for a much higher ease of use compared to the joint control scheme that had previously been implemented. Despite the nature of the 4-bar linkage used to create the current arm, it was still be modeled as a serial chain manipulator with the assumption that the third joint rotation was simply the same as the second joint rotation in the opposite direction.

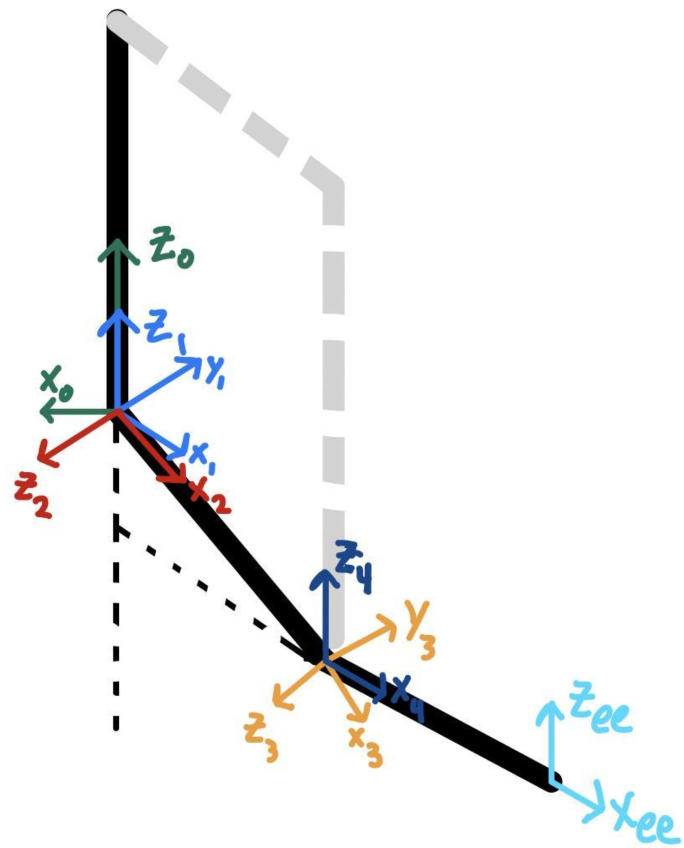


Figure 6.10: Frame assignments

The modeling of this arm was done using transformation matrices to assign frames at each joint along the arm, which allows for knowing the position of each joint with respect to the base frame. Each of these 4x4 transformation matrices consists of a 3x3 rotation matrix which depicts the orientation of each frame with respect to another, as well as a 3x1 column vector which details the position of the frame in cartesian space. An example of this transformation can be seen in equation 1 where T is the transformation matrix from the base (0) to first (1) frame, and θ_1 (the angle about the Z-axis). All equations in this section are referenced from John Craig's *Introduction to Robotics: Mechanics and Control* [10]. By chaining these transformation matrices together (equation 2), it was possible to determine the XYZ position of the end effector with respect to the base of Nautilus (equations 3-5). It should be noted that in equation 5 the simplification of θ_2 & θ_3 was not carried out due to the fact those terms must be retained for the Jacobian calculations. These assignments also allowed for the determination of the Denavit-Hartenberg parameters that define the given arm which can be seen in Table 6.1. Furthermore, this allowed for modeling the arm in different poses through MATLAB as seen in Figure 6.11.

Table 6.1: DH parameters of 4-bar linkage arm using the modified *Denavit-Hartenberg* parameters

DH Parameters	α	a	θ	d
1	0	0	θ_1	0
2	$\frac{-\pi}{2}$	0	θ_2	0
3	0	$L1$	θ_3	0
4	$\frac{\pi}{2}$	0	θ_4	0
ee	0	$L2$	0	0

$$ {}_{1}^{0}T = \begin{bmatrix} \cos\theta_1 & \cos\theta_1 & 0 & 0 \\ \cos\theta_1 & \sin\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{(eq. 1)} $$

$$ {}_{ee}^{0}T = {}_{1}^{0}T\,{}_{2}^{1}T\,{}_{3}^{2}T\,{}_{4}^{3}T\,{}_{ee}^{4}T \quad \text{(eq. 2)} $$

$$ X = \frac{L1}{2} cos(\theta_1 + \theta_2) + \frac{L1}{2}\cos(\theta_1 - \theta_2) + L2\sin(\theta_1 + \theta_4) \quad \text{(eq. 3)} $$

$$ Y = \frac{L1}{2} sin(\theta_1 + \theta_2) + \frac{L1}{2}\sin(\theta_1 - \theta_2) + L2\sin(\theta_1 + \theta_4) \quad \text{(eq. 4)} $$

$$ Z = -L1\sin(\theta_2) - L2\sin(\theta_2 + \theta_3)\cos(\theta_4) \quad \text{(eq. 5)} $$

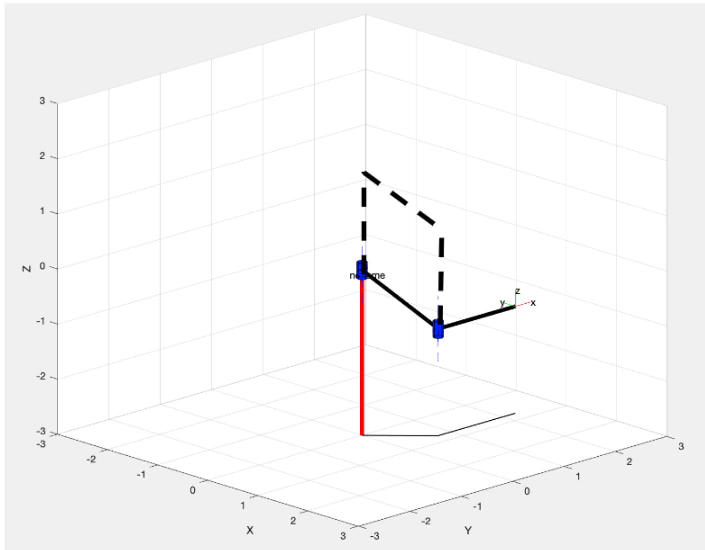


Figure 6.11: MATLAB model of arm, 4-bar linkage superimposed with dashed lines

Since these equations detail the position of the arm with respect to the joint angles, in order to position the arm above a sample in-situ, the exact XYZ position would need to be known, allowing for an inverse kinematics calculation which would determine the joint angles to send to the servo motors. Since this method of control is highly impractical, velocity control was implemented which allowed the user to move the endpoints position with respect to time by sending a $\frac{dx}{dt}, \frac{dy}{dt}, \frac{dz}{dt}$ input. To relate the velocity input to the joint angles, the Jacobian matrix was used. Since the input is a velocity vector, it was necessary to take the inverse of the Jacobian and multiply it by the velocity vector which yielded the rotational velocities for each joint. Equations 6 and 7 show the relationship between a Cartesian endpoint velocity and the joint velocities where $\dot{\theta}$ is the joint angle vector, $\dot{X}$ is the velocity input vector, and J is the Jacobian Matrix.

$$\dot{X} = J\dot{\theta} \qquad \text{(eq. 6)}$$

$$\dot{\theta} = J^{-1}\dot{X} \qquad \text{(eq. 7)}$$

The Jacobian matrix is determined by the degrees of freedom (DOF) and number of actuated joints. Since the arm to be controlled is a 3DOF arm and has 3 actuated joints, the Jacobian matrix takes the form of a 3x3.

$$J = \begin{bmatrix} \frac{\partial x}{\partial \theta_1} & \frac{\partial x}{\partial \theta_2} & \frac{\partial x}{\partial \theta_4} \\ \frac{\partial y}{\partial \theta_1} & \frac{\partial y}{\partial \theta_2} & \frac{\partial y}{\partial \theta_4} \\ \frac{\partial z}{\partial \theta_1} & \frac{\partial z}{\partial \theta_2} & \frac{\partial z}{\partial \theta_4} \end{bmatrix} \qquad \text{(eq .7)}$$

Using these calculations, it was possible to create a Simulink model to determine the performance of the arm. The method of input was an Xbox controller which allowed for sending a velocity input in real time to model the linear cartesian motion of the arm endpoint.

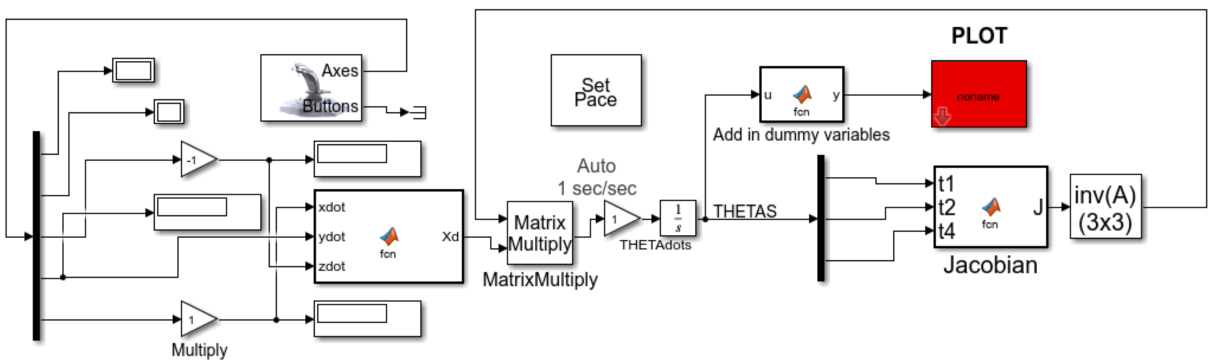


Figure 6.12: Simulink control model

Using this model (Figure 6.12), it was possible to simulate the motion of the arm in XYZ space (Figure 6.13), validating the model and calculations for implementation on hardware.

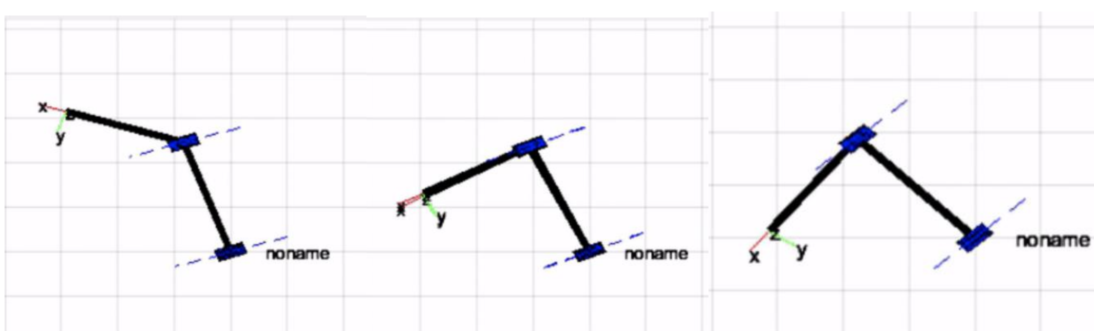


Figure 6.13: Snapshot of linear motion of arm in simulation

Section 7: System Integration and Testing

Fully iterated, finalized subsystems were assembled in Santa Clara University's RSL before being transported to multiple locations for underwater testing. The soft gripper, our first completed component, was rigorously tested out of water with a variety of objects. The finalized version of our stereolithography end effector was then put through a cycle test to ensure durability. Next came the robot arm itself, with all of its necessary servo housings, gears, and power cables. Several electronics issues later, the group had a fully powered arm ready for a full test. Nautilus, however, required time-consuming ballasting and water-proofing operations that added several steps to this process. After ensuring full functionality our the ROV, the team deployed Nautilus four times in an RSL "Garage" test tank (Figure 7.1) and once at the large MBARI test tank (Figure 7.2). In the smaller garage tank, ten full sample retrieval tests and various other operations were performed.

Figure 7.1: RSL Garage test tank

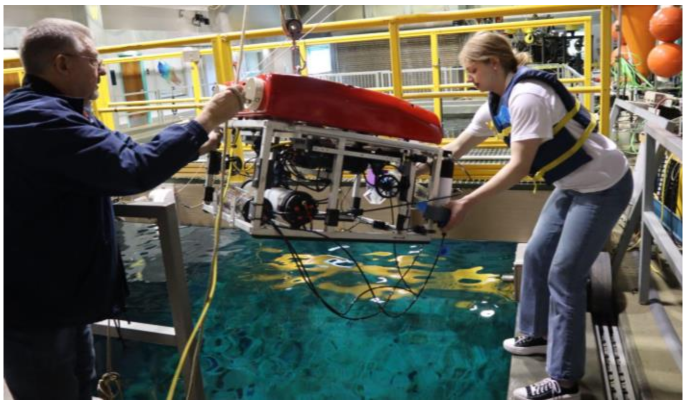


Figure 7.2: MBARI test tank

7.1 Operating Nautilus

Separate from the functionality of our robot manipulator, underwater operation of electronic systems poses many challenges. Nautilus has three water-tight electronics housings, each with cable penetrators. Pictured in Figure 7.3, O-rings secure the ends of these cylinders, while epoxy seals each penetrator. Unfortunately, the epoxy deteriorates with time, thus putting the valuable contents of the tubes at risk. The high pressures of deep water threaten leaks significant enough to damage the electronics inside. As such, epoxy touch-ups and constant verification of our watertight seal were necessary for each deployment. Included in our standard operating procedure, operators must use vacuum pumps to test each electronics tube. Pressurize the tube to 15 inHg, then observe the pressure drop. Losses of less than a 1 inHg in five minutes marks a successful seal verification, labeling that tube as water-ready.

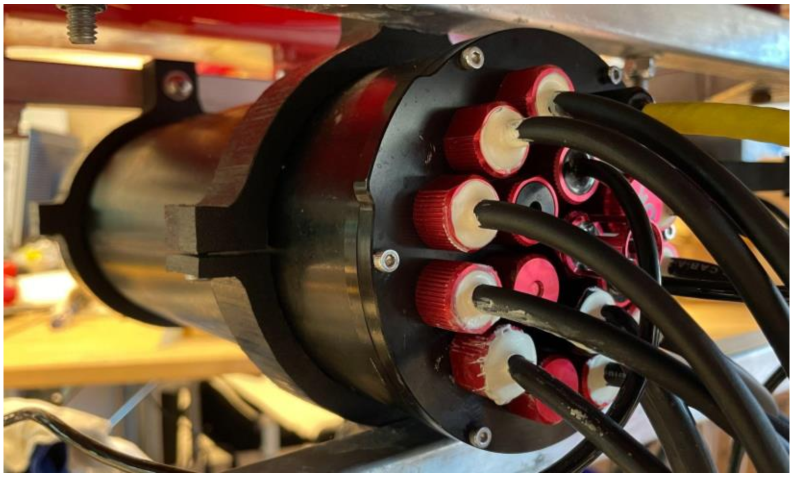


Figure 7.3: Electronics tubing on Nautilus ROV

Equally important is the practice of ballasting Nautilus. Without proper dive weights, the thrusters cannot overcome the ROV's positive buoyancy. Unable to ballast in our shallow Garage test tank, this issue was only encountered at MBARI. Here, nearly 40 lbs. of additional weight was needed to properly ballast the ROV. In the future, Nautilus needs to be fitted with dive weights that attach to the frame (rather than the top) of the ROV, something that already exists in RSL. Again, this issue is eliminated with the use of our standard operating procedure (Appendix A) and deployment checklist (Appendix B), documents that did *not* already exist when the group inherited Nautilus.

7.2 Test Procedures

In lieu of the full SOP, offered here is a brief summary of our testing procedures and an overview of those conducted at each location. As detailed in previous sections, properly ballasting, sealing, and connecting Nautilus to the topside laptop is the first step in any deployment. From here, power is supplied to both the ROV and robot manipulator in the form of LiPo batteries. For a test inside the lab (Garage tank), one battery is required for the ROV and one is required for the manipulator. For a test outside the lab (MBARI tank), where Nautilus can submerge and drive around, three LiPo batteries are required for the ROV. This will afford users a total deployment time of approximately 45 minutes.

Now, the arm is assembled, and servo home positions are set. It is favorable to partially attach the arm such that no gears are engaged, but where servos are still connected to their respective power cables. Here, servos move freely to their home positions, thus ensuring the correct ranges for all three joints once the arm is fully built. Next, the ROV is placed into the water with a dedicated team member supporting the arm while it is above water. Finally, testing can commence (Figure 7.4).

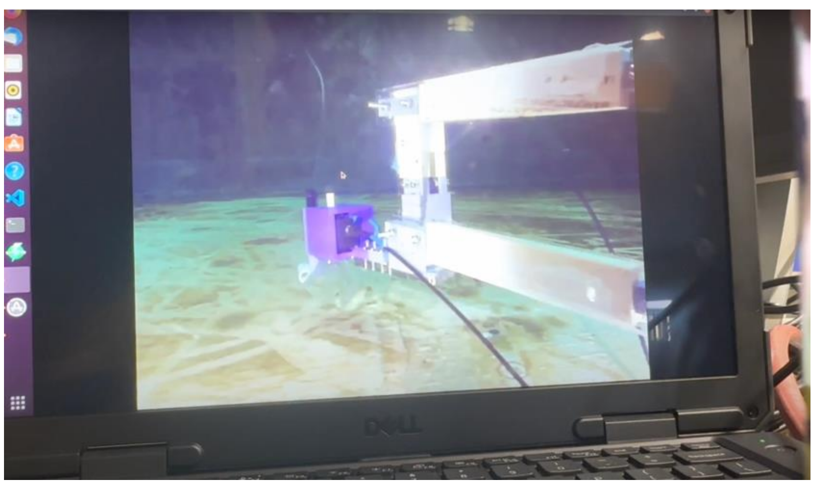


Figure 7.4: Nautilus top-side camera feed at MBARI

7.3 Data & Results

While the majority of our testing was performed in the Garage test tank, our MBARI deployment best simulated real-world conditions. Here, we encountered the biggest issue with our design, namely gear slippage. The process of submerging and driving Nautilus exerts enough force on our manipulator to make the gears slip unintentionally, thus throwing off our rotational ranges. For instance, the vertical gear connection (joint #2) slipped when the thrusters were fired downward to sink the ROV. Joint 1 similarly slipped when driving Nautilus backwards and forwards. To be clear, nothing on the manipulator breaks when this occurs, but the ranges of motion of our joints become limited when this occurs. Possible remedies for this issue are two-fold. First, the transmission itself needs to be more robust, eliminating any displacement of the gears that allows the slippage. Right now, the arm is made entirely of 3-D printed and laser-cut parts, and such methods always induce some error. The second possible solution includes a separate actuated "sling" that holds the manipulator against the ROV's frame while it moves. Here, Nautilus would maneuver over to a sample and the actuated sling would release the arm to perform its full functionalities. During our MBARI deployment, however, this gear slippage issue persisted, preventing the group from completing a sample collection process (Figure 7.5).

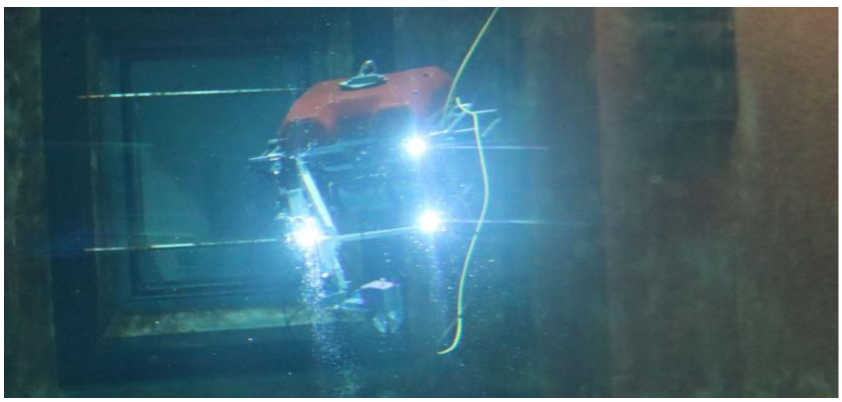
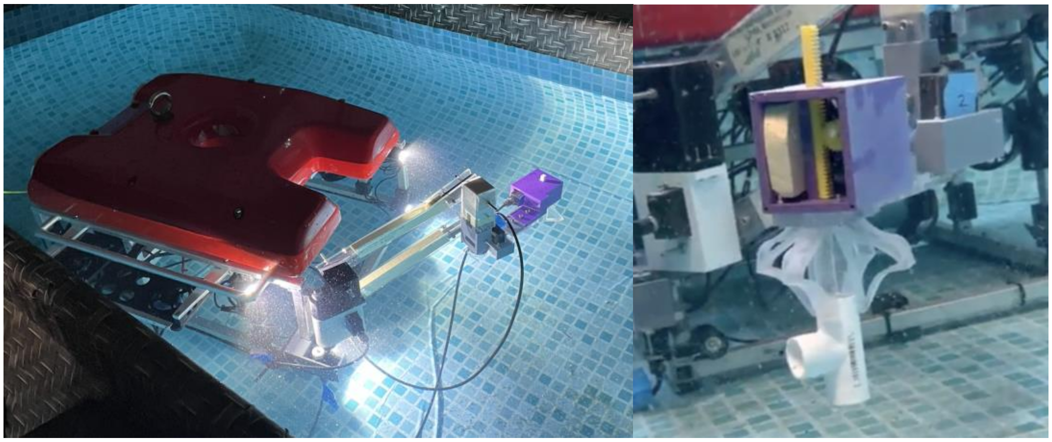


Figure 7.5: Nautilus deployment at MBARI

Despite the shortcomings during our MBARI deployment, testing at the Garage test tank was hugely successful. In this environment, Nautilus has limited mobility, which eliminated the possibility of gear slippage, thus allowing us to focus only on the manipulator. Over the course of several deployments, 10 full sample collection tests were performed, each boasting impressive reliability. Two types of processes were used, denoted by the methods of operation. It took an average of 48 seconds to retrieve our sample when the operator was looking straight into the pool, while it took roughly 2:30 when the operator was looking only through the Nautilus camera with the lights off. This time discrepancy is largely due to a camera delay of over a second. Even with this delay, however, the operator properly centered the end effector over our sample in an average of 1.8 attempts. Through the use of our laser pointer, this centering process never took more than 3 attempts. As stated, all of our full sample collection tests were successful in placing our PVC specimen into the intended storage compartment. Most notable, however, is our grip retention rate of 100%. Once centered and gripped, our end effector had *zero* unintentional drops. With the sample in the gripper, we swung the arm through its full ranges of motion and still encountered zero drops. The only drops recorded in any of our testing were *intentional* drops into our storage system. Simply put, our soft gripping end-effector was extremely effective in retaining samples, even in a variety of specimen orientations (Figure 7.6).



Figures 7.6: Nautilus deployment (left) and gripped sample (right) at the Garage test tank

Finally, it is important to report on metrics separate from our typical sample retrieval process. Each arm joint boasts a range of 130° and a rotational speed of about 1 rad/s. Together they combine for a total workspace of 2.5 ft^2 (Figure 7.7). Equally important is our verification of the arm's neutral buoyancy, critical because we do not want to affect the positive buoyancy of Nautilus itself. In closing, the testing of our full system verified all of our main system requirements within the confines our the Garage test tank.

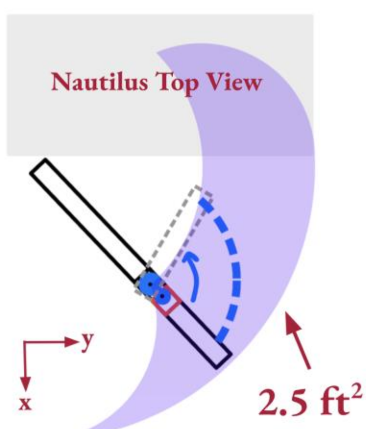


Figure 7.7: Graphical representation of the Nautilus workspace

Section 8: Professional Considerations

Aside from technical prowess showcasing rigorous engineering practices, this project must remain rooted in safety, usability, and ethical consideration. System serviceability should be measured by the ability to repeat the group's successes, something that can only be ensured with these critical pillars to follow. The system fails if it is not safe. It fails if it is not usable for future owners. And it fails if it does not maintain an engineering ethical examination in line with the views of Santa Clara University.

8.1 Safety Guidelines

The Robotics Systems Laboratory and School of Engineering each have important safety rules that guided the project's scope, fabrication, and testing (Appendix D). The RSL offers and requires LiPo safety training for any individuals using these batteries due to their dangerous volatility. Additionally, both institutions maintain stringent guidelines for marine operations to combat the inherent danger of oceans and lakes.

The mishandling of Lithium-Polymer batteries can result in fire, explosions, or permanent damage to the battery. They boast impressive capabilities, such as constant discharge and low degradation, but strict regulations must be followed to maintain safety of use. Constant monitoring of their voltage is the most basic requirement, as each battery cell must always be between 3.2 and 4.2 volts. Draining below or charging above these levels can result in the aforementioned risks. To mitigate these dangers, each battery cell must be checked frequently and stored in specific environments. When not in use, each LiPo is placed in a fire-safe container. When traveling, the LiPo rests in a fire-safe bag inside of an ammo crate (Figure 8.1). Finally, any charging of a LiPo battery must be done with direct supervision from a group member.

Figure 8.1: LiPo battery properly stored in multiple fire-safe containers

Once these batteries are safely secured, students must adhere to marine operations guidelines during deployments to areas such as Lake Tahoe and Monterey Bay. Moving Nautilus above water is a complicated maneuver that requires multiple team members. The vehicle is heavy, and an uncoordinated movement could result in physical injury or a cold-water bath. Simple combatants to this risk include wearing life jackets at all times as well as establishing specific roles for each group member.

8.2 Usability

Before the system can perform its underwater functionality, it must be assembled and lowered into the test area. Luckily, our 4-bar linkage arm is able to hold itself up through the simple use of a simple zip tie. This greatly reduces the time required to erect the system. Nautilus, however, weighs 180 lbs., a number that only increases with dive weights and water mass. As such, the usability of our system includes the ability to safely position the ROV into the water. At the Garage, three students were required to lift and place the ROV into the test tank. At MBARI, where additional dive weight is required, a crane was used to raise and lower the ROV into their large test pool (Figure 8.2). In both cases, an additional team member must support the arm during the process.

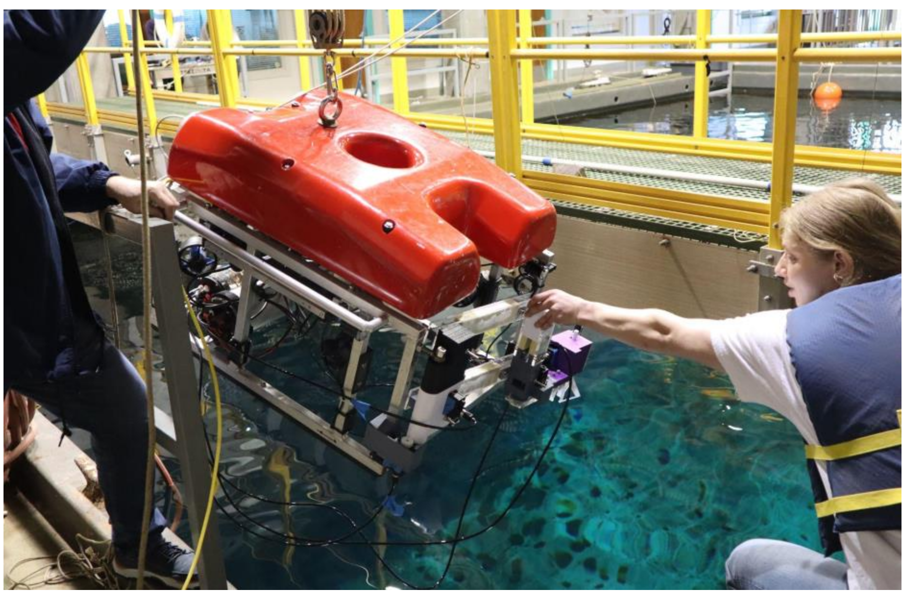


Figure 8.2: Deploying Nautilus via crane method at MBARI

Once in the water, the Nautilus ROV Robot Manipulator System operates with a top-side laptop connected to two gaming controllers. One operator uses a controller to control the movements of Nautilus, while the other commands the manipulator itself (Figure 8.3). The software streamlines user efficiency, employing natural controls for each function. For instance, the controller's “d-pad” is linked to the expected horizontal and vertical moments. Here, the group is confident that new users can operate Nautilus without rigorous explanation and practice. Again, the Nautilus standard operating procedure and deployment checklist will be made available for future groups (Appendices A and B).

Figure 8.3: Two Nautilus operators at MBARI deployment

8.3 Ethics

As Santa Clara University students, we understand that we have a duty to serve our community as engineers. Ethical considerations must be at the forefront of all innovation in order to preserve the innate human dignity of all individuals. This responsibility dictates the need for informed consent in order to allow individuals the freedom to choose which risks they are subjected to. While many projects may not outwardly appear to hold great significance in the moral evolution of our society, there are a myriad of considerations that must not be overlooked to ensure the project promotes ethical decision-making.

One of the main areas that our project focuses on is the ethical research and study of the world around us. Why should we divert resources to researching the world's water bodies, and spend our time developing tools that these researchers can use?

There are many reasons why the exploration of the ocean (and other bodies of water) are important. For example, we as humans take many resources from the ocean, and oceanographic studies are imperative to understanding how we can best and most sustainably manage those resources, so they remain for future generations. Continued exploration of our oceans has the potential to bring us new sources of medical, technological, and ecological breakthroughs, which might help us solve some of the world's greatest challenges. Overall, using the lens of the common good, we can see how studying the water around us can help improve the lives of everyone, and thus we are ethically justified in supporting this research.

Our project has taught us lessons about sustainably conscious engineering and shown us the importance of deeply considering our application and what it implies. Since we are designing something to be actively used underwater, we must consider how our materials will interact with the lakes and oceans that are being studied. Polluting these bodies of water, whether via leaving parts and pieces of the robot behind, leaching harmful chemicals from our chosen materials into the body of water, or other means, is unacceptable. Thus, we are working diligently to think critically about the engineering choices we are making and how those choices will affect the greater world around us. Overall, our project teaches us about the characteristics that make a good engineer through the environmental considerations we have to make when designing the robotic arm.

This leads to the ethical pitfalls of our project. As stated above marine research presents a next positive effect to the common good; however, it also has potential to harm our oceans and have a negative impact on ecosystems, resources, and more. Marine research must be conducted in a way that minimizes the impact of scientists and researchers on the natural environment so as not to disturb the delicate balance of an ecosystem and the living organisms within it. By creating and designing marine ROVs we risk polluting the waters we wish to study. It is also worth noting that fabrication of a robotic system like this poses risks to us, which we all work actively to minimize by following lab guidelines and rules.

Section 9: Project Summary

9.1 System Evaluation

The scope of this senior capstone project consisted of three major goals: creation of an underwater robotic manipulator, creation of a soft gripper end effector for said manipulator, and creation of a cartesian endpoint control scheme. For the end effector we developed a fully functional soft gripper capable of delicately recovering samples of irregular shapes while being durable enough to withstand a minimum of 500 cycles. The 4-bar linkage arm was able to position the arm above a sample within Nautilus' field of view and place it into a storage system in multiple tests. Furthermore, it was proven that this ROV and robotic arm system was capable of being operated in dark underwater conditions, with manipulation taking place solely through the ROV's camera. The team also successfully tested a cartesian endpoint control scheme which allowed for limited linear motion of the endpoint.

9.2 Future of Nautilus in RSL

At the outset of this project, it was understood that many possible improvements to the Nautilus ROV system would fall outside the purview of this undertaking. Furthermore, as the development and testing of the Nautilus Robotic arm went on over the course of the past year, more potential improvements came to light. The goal of this section is to highlight these items that could greatly improve the usability of Nautilus which fell outside of the current group's work.

In regards to the Nautilus ROV itself, many quality-of-life improvements could be implemented which would allow for easier deployment, testing, and use. The ability of the three pressure vessels, which held all of Nautilus' electronics, to remain watertight, was the first and most obvious issue that the team encountered. These water leaks were stymied by replacing select penetrators with newer BlueRobotics Wetlink Penetrators (in the case of the pressure vessel for the arm) or epoxied (in the case of the main electronics tube). As testing progressed throughout the year, it became apparent that due to the nature of how the epoxy penetrators were originally implemented, they were not a viable long-term solution for waterproofing the electronics. It is our opinion that the best long-term solution for waterproofing would be to completely transition to Wetlink Penetrators instead of epoxied connections.

As for the software and control subsystem, many optimizations can be made. The camera located in the central electronics tube allows the operator to identify and locate objects of interest to be manipulated by the robotic arm. Due to the dynamic nature of the marine environment, it is essential that there be little delay between what is happening underwater and what is seen topside. Via testing, it was determined that the delay from Nautilus' camera to topside was roughly 2 seconds. This delay is not practical for control of either the arm, nor the ROV itself, but we believe that this delay can be improved based on the delay of the RSL's BlueROVs which operate with the same camera and tether setup. The cartesian endpoint control could also benefit from an increased range in servo rotation. The servos utilized ended up being the SER-110X from BlueTrail Engineering, due to issues with programming the SER-120X servos to allow for a larger range of motion. Through the use of these 120X servos, it should be possible to greatly expand the workspace of the arm. Furthermore, fixing the implementation of heading control for the ROV could make control of the arm much more efficient as it could mitigate the coupling effect by which the arm moves the ROV itself while it tries to move.

For the arm, future iterations could greatly benefit from the lessons learned based on this prototype. For starters, a more rugged design would greatly improve the deployment ability of the ROV with arm attached. In its present state, gear slippage is a major issue which was prevented with a "sling" that held the arm in place while being placed in the water. A more rigid arm would be designed with the goal of completely preventing gear slippage in the first place. Other improvements for this subsystem would also include making the attachment for the arm electronics more accessible, as well as making the next iteration of the arm more hydrodynamic.

Higher level goals that are left to the future of the RSL include increasing the capabilities of the arm including modular grippers, additional modular end-effectors, vision-based object capture, haptic interfaces, and integrated vehicle/arm dynamic control.

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Appendices

Appendix A: Nautilus ROV Robot Manipulator Standard Operating Procedure

Preparation & Assembly

(3 people required)

1. Remove LiPo Batteries to be used from the storage box.
2. Read LiPo Battery charge. Charge or discharge as needed to reach 4.2V for use.
3. Add LiPo Battery to clear tube and ensure circuit connections are sound
4. Add LiPo(s) to the metal tube and verify connections. Pool testing requires only one LiPo to power thrusters, for longer deployments 3 LiPo batteries are required.
5. Pressurize all tanks to verify the seal
6. Secure tubes to frame
7. Attach trapezoidal arm links to Nautilus Frame
8. Secure arm sling to protect arm while out of water
9. Disengage Servo gears (to prevent unexpected arm movement at power start)
10. Connect Cables to Servos and verify amperage draw is as expected (<1A)
    a. Joint 1 Servo connects to Cable 1
    b. Joint 2 Servo connects to Cable 2
    c. Joint 3 Servo connects to Cable 3
    d. End Effector Servo connects to Cable 4
11. Confirm servo starting angle is as desired
    a. Cable 1 Starting Angle 285
    b. Cable 2 Starting Angle 190
    c. Cable 3 Starting Angle 310
    d. Cable 4 Starting Angle 210
12. Attach final arm link and end effector
13. Engage arm and end effector gears and attach to Nautilus
    a. End Effector Starts in Neutral position
    b. Trapezoid Link Starts a few degrees away from flush with the frame

c. Vertical Link Starts in Neutral (with zip tie support)
d. Last link starts parallel to trapezoid link

14. If the red buoy is already attached, skip to step 21.
15. Place 6 washers, 6 spacers and 6 smaller screws in designated holes in the floatation top.
16. Two people align and set floatation on top.
17. Additional people align screws into washer/spacers and Nautilus frame.
18. Tighten with an 11mm wrench and torque wrench.
19. Place the large screw through the floatation top and frame. Tighten manually.
20. Verify power connection to thruster and arm servos

Launch

(4 people required)

1. Extend thruster wings on either side of the Nautilus frame.
2. Verbally walk through the plan to launch Nautilus with group members.
3. Carefully place Nautilus in the water.
4. If ballasting is required, add dive weights as necessary.
5. Remove arm sling once Nautilus is fully submerged.
6. ALTERNATIVE: If facility allows, use a crane for launch.

Operation

(3 people required)

1. One person uses the Xbox controller to control Nautilus orientation and movement.
2. A second person uses the second Xbox controller to control arm and gripper movement.
3. One person manages the tether. Take care to avoid tangling the tether.
4. SUGGESTED: Additional people can position the object on fishing line for collection, document robot movement, and monitor for damage or collision.

Post-Operation Retrieval

(4 people required)

1. Return Nautilus to the launch area.

2. If the thruster LiPo power is drained, wait for the robot to surface and guide back to the launch point gently with the tether.
3. Verbally walk through retrieval with group members.
4. Carefully remove Nautilus from water.
5. ALTERNATIVE: If facility allows, use a crane for retrieval.
6. Pat dry with towels.
7. Allow to dry completely.
8. Verify that the LiPo storage tube is completely dry and there is not any water dripping near the tube opening.
9. Open LiPo storage tube and remove LiPo holster.
10. Unplug LiPo batteries. Move away from water.
11. Dry holster completely. Verify there is no water in or around the tube. Close tube.
12. Check LiPo voltage. Charge or discharge to reach 3.7 Volts for storage.
13. Store LiPo batteries according to safety protocol.
14. Avoid opening the camera or electronics tube if possible until Nautilus has been completely dried.
15. Verify tether is wrapped around the spool and not tangled.
16. If testing in a saltwater tank, seal tubes and protect exposed electronics before rinsing all parts with fresh water.

Appendix B: Nautilus Robot Manipulator Deployment Materials Checklist

ROV Items

- Nautilus Frame and Buoy
- Cart
- Tether and Spool
- Dive Weights
- LiPo Batteries (x2 for lab test; x4 for outside deployment)
- Vacuum Pumps (x2)

Manipulator Items

- Arm (With transportation protection)
- End Effector
- Connecting Hardware (Screws, Spacers, Nuts)
- Xbox controllers (x2)
- Laptop
- Blue robotics control box
- Duplicate gripper
- Extra gears

Tools

- Socket Wrench with 3/4" attachment
- 3/4" Wrench
- Allen Key Multitool
- Needle nose pliers
- iFixIt Screwdriver set

Miscellaneous

- Extra Nuts, washers, screws
- Extra Cables

- Extra Foam
- Zip Ties
- PVC collection sample (on fishing line)
- Life Jackets
- Duct Tape

Appendix C: Mock-Ups and Prototypes

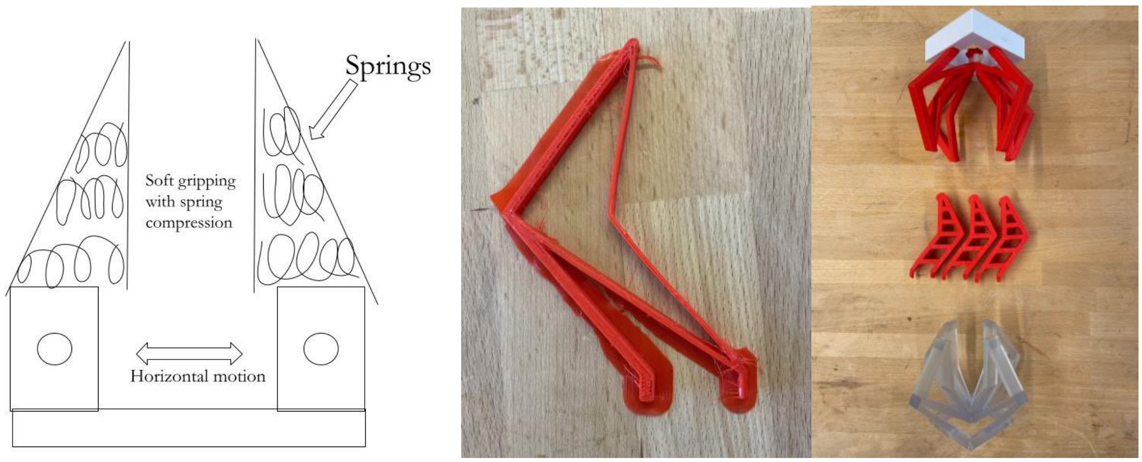


Figure C.1: Initial prototyping of the soft gripper

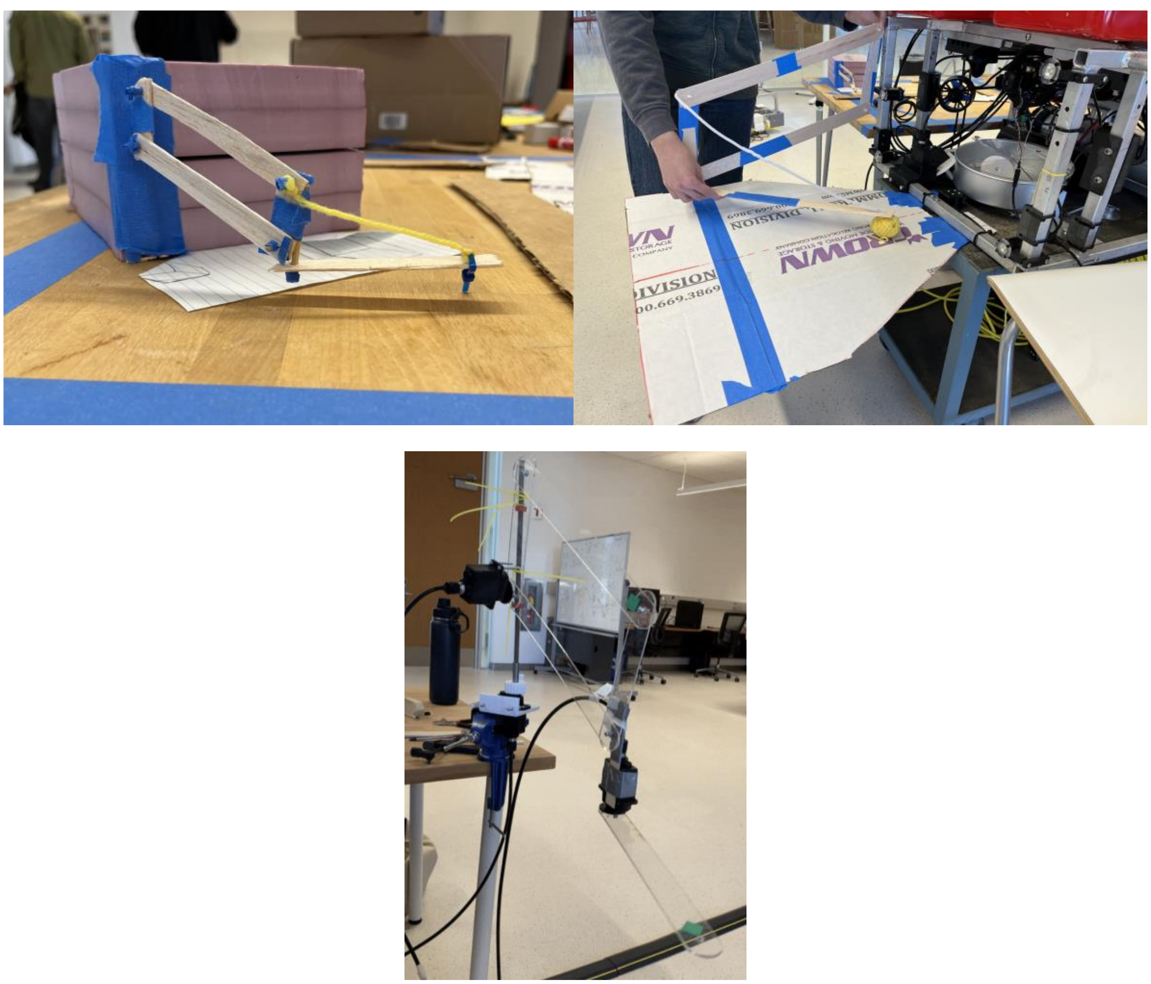


Figure C.2: Initial prototyping of the robotic arm

Appendix D: Student Project Hazard Assessment Form

Project Title: RSL Nautilus Mechatronic Arm and Sample Storage
Project Team Members: Dana Stefanides, Rebecca Walters, Andrew Stewart, Steven Reimer, Jenny Huynh, Andy Nguyen, Matt Hayes
Project Advisor **Name**: Dr. Christopher Kitts **Department**: Mechanical Engineering **Phone**: EXT -4382 **Email**: ckitts@scu.edu
Proposed Project Location(s) (Department, building, room#): SCDI RSL and SCU Garage
Anticipated Dates of Project Duration: 9/19/22 to 6/15/22
Summary of Project Objectives: Come spring quarter, the system must collect multiple samples in a submerged environment. It must then place those samples into separate, enclosed containers for storage (up to 4). The system must be able to capture these samples and return them to the surface within a 45-minute mission. Finally, there must be a record of the location each sample was taken. All of this must be built, tested, iterated upon, and finalized within a $5,500 budget.

Hazard Checklist:

HAZARDOUS CONDITIONS/PROCESSES/ACTIVITIES
Electrical Hazards Mechanical Hazards Physical Hazards ✓ Power tools and equipment ✓ Extreme temps (high temp fluids: water > 160 °F, steam, hot surfaces) ✓ Machine guarding/power ✓ Batteries ✓ Material handling of heavy objects; rotating parts, pinch points ✓ Robotics ✓ Sharp Objects
Reaction Hazards Hazardous Processes Other Hazards ✓ Explosive (gases, aerosols, or particulates) ✓ Exothermic, with potential for fire, excessive heat ✓ Metal Fabrication (welding, cutting, drilling, soldering, etc.) ✓ Construction/Assembly, etc.

Hazard Checklist (continued)

HAZARDOUS AGENTS
✓ Explosives ✓ Flammables

Manufacturing:

Hazardous Activity, Process, Condition, or Agent *Manufacturing*
Summary of Procedure or Tasks: Some of the parts used in this project will be machined ourselves. This involves cutting, drilling, and facing parts in the machining lab. All of the mechanical engineers in the group (six members), will have completed Mech 101L by the end of the Fall 2022 quarter and will subsequently have experience using bandsaws, lathes and drills.
Describe Hazards: Such machines have the ability to severely injure the user if operated improperly. Metal chips, long hair or lanyards getting caught in the machine, or other improper contact with the machine can result in such injury.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): The machine shop guidelines will be followed at all times. Only certified users will go into the lab and nobody will ever work alone. All users will wear PPE glasses, long pants, and closed toed shoes at all times. There will be no loose clothing, long hair, jewelry, or lanyards that can potentially get caught in the machines. Only one person will operate each machine at a time and work pieces will always be treated as hot and sharp. Next, machines will always be checked for functionality and guards will be in use while they are on. Finally, lab manager and SCU safety information will always be on hand.

Assembly:

Hazardous Activity, Process, Condition, or Agent Wiring/Electrical Components
Summary of Procedure or Tasks: The Nautilus ROV runs on two parallel 16.9V Li-ion batteries. Additionally, the robot arm and storage system will be powered by another battery inside the ROV. These additions will also require a separate microcontroller that will receive code from the original Nautilus Arduino. Both the robot arm battery and microcontroller are fully removable, making testing possible without the Nautilus ROV.

Describe Hazards: There is always a risk of electrocution and damage to electric components when dealing with electronics. When making the circuits, burns of heat guns as well as inhaling fumes from soldering are additional hazards.
Hazard Control Measures: There are several safety protocols for electrical soldering. First, safety glasses, insulated gloves, long pants, and conductive shoes must be worn. The circuits must be fully unplugged and powered off while changes are being made. The transportation and storage of LiPos must be done in a fireproof container. All electronics must be used in dry, clean, and organized conditions. Finally, students must utilize proper Lipo Safety Training from ENGR 180 and check for damage in the circuits and batteries before each use.

Hazardous Activity, Process, Condition, or Agent Mechanical Assembly (Pinch Points)
Summary of Procedure or Tasks: Power tools are necessary to assemble the robot arm and storage system.
Describe Hazards: Risk of injury is always pertinent when dealing with motorized tools. Clothes and body parts are at risk of being caught in the tools or between parts. They can be cut or pinched, resulting in personal injury and/or damage to the equipment.
Hazard Control Measures: PPE glasses, long pants, closed-toed shoes, and no loose clothes, hair, or strings are some of the personal measures taken by students using power tools. All assembly and power tool instructions will be followed. Additionally, training and experience with power tools from Mech 101L is invaluable in reducing these risks.

Testing and Operation:

Hazardous Activity, Process, Condition, or Agent Electrical Components in/near water
Summary of Procedure or Tasks: There are three main components of the Nautilus ROV to check. The main Nautilus controls, the main Nautilus battery, and the additional robot arm appendage. This appendage includes the robot arm itself, the storage system, and the waterproof

case holding the microcontroller and battery.
Describe Hazards: Water and electronics don’t behave well together. Live circuits can be damaged or shorted if not properly sealed.
Hazard Control Measures: To mitigate this risk, all electronics must be fully enclosed in waterproof cases and all seals must be checked before deployment. Then, they must be rechecked as this is the most important factor. The ROV circuits must not be interacted with while live and they must not be checked while near water. Finally, leak sensors can be added to the electrical cases and watertight enclosures can be thoroughly dried after a mission/test before being opened.

Hazardous Activity, Process, Condition, or Agent Motorized Arm
Summary of Procedure or Tasks: Testing the robot arm will involve motorized metal parts that move in multiple directions and with grappling motions. In addition, the Nautilus ROV has thrusters that spin at high speeds.
Describe Hazards: Accidental contact with the moving parts of the ROV servo motors or robot arm motors can result in damage to the equipment and injury to a person.
Hazard Control Measures: PPE gloves, safety glasses, long pants, closed-toed shoes must be worn. More specifically, avoid loose elements on your person to avoid them getting caught. All members must know the testing procedures and be weary when the ROV is starting up. Announce all tests loudly to the group.

Hazardous Activity, Process, Condition, or Agent Launching and Recovering the ROV
Summary of Procedure or Tasks: The ROV is over 100 pounds and requires lifting on and off the edge of a boat for a given deployment.

Describe Hazards: Lifting such a large payload can result in injury or falling off the boat. Additionally, mud, silt, or rocks can weigh down or make the ROV stuck at the sea floor.
Hazard Control Measures: Be sure to lift with your legs and do not overexert yourself. Be cautious of your surroundings and give people a safe distance so nobody falls off the boat. Be wary of rocky areas where the ROV can get stuck and always use a robust tether to pull the ROV to the surface if it loses buoyancy.

Hazardous Activity, Process, Condition, or Agent ROV Loss Prevention
Summary of Procedure or Tasks: The rov will be out of sight and descending to a max of 100 m connected to a single tether
Describe Hazards: Risks involved include tether becoming tangled or severed, as well as power loss to the rov.
Hazard Control Measures: To prevent loss of the rov will utilize high density foam to ensure positive buoyancy in the event of power loss or tether disconnection. One team member will be assigned to monitor voltage levels to ensure the rov returns before power loss.

Hazardous Activity, Process, Condition, or Agent ROV Battery
Summary of Procedure or Tasks: The rov and arm are powered by 2-3 LiPo batteries.
Describe Hazards: LiPo batteries carry the risk of heating up, swelling, catching fire, and or bursting if not properly used, stored, or transported.
Hazard Control Measures: LiPo batteries will be transported in fire resistant bags/containers, including ammo boxes that the rsl currently utilizes to transport LiPos. Batteries will be stored in fireproof lock boxes at 3.8 volts. The batteries will be checked before and after use for any damage. Fire extinguishers and sand will be on hand in the event of a fire

Hazardous Activity, Process, Condition, or Agent ROV Lights and Lasers for Distance
Summary of Procedure or Tasks: The rov is equipped with bright lights and lasers to observe the position of the robotic arm's end effector
Describe Hazards: Bright lights and lasers have the potential to damage a person's eyes
Hazard Control Measures: Lights and lasers will only be operated when pointing away from people and will not be used near any reflective surfaces. Lasers will only be used underwater

Hazardous Activity, Process, Condition, or Agent ROV Collision Prevention and Boat propellers
Summary of Procedure or Tasks: The ROV will be in operation near the boat it is tethered to and within range of the propellers during launch and recovery. The underwater environment is highly uncertain and ROV may surface in an unexpected location.
Describe Hazards: The ROV may collide with the boat or propellers which can damage the ROV, arm, or boat. There is also a possibility that the tether becomes tangled or gets caught in the propeller.
Hazard Control Measures: The ROV will be piloted with extra care especially during launch and recovery. When surfacing the ROV, aim to spot the ROV from far away before steering it near the boat.

Hazardous Activity, Process, Condition, or Agent Boat Safety
Summary of Procedure or Tasks: ROV testing missions require the use of a boat in which case the boat propellers must be considered.

Describe Hazards: The boat propellers can cause injury to any individuals in the water or damage to the ROV or tether. In addition, individuals on the boat during testing missions can fall in or get seasick, in addition to the risk faced in the event of a fire or other incident which damages the integrity of the boat.
Hazard Control Measures: All boat testing missions will be accompanied by an experienced boat driver and propellers will be turned off when not in use. Guidelines by the California DBW will be strictly followed including life jackets.

Transportation and Storage:

Hazardous Activity, Process, Condition, or Agent ROV Weight
Summary of Procedure or Tasks: The ROV weighs over 100lb and requires students to manually lift the ROV in/out of transportation vehicles, boats, and the water.
Describe Hazards: Students can become injured when attempting to manipulate heavy weight including back injuries. Furthermore, appendages can be pinched or crushed by the ROV if care is not taken. Dropping the ROV can cause serious injury and serious damage to the equipment.
Hazard Control Measures: The ROV will remain on its roller cart whenever possible and be transported with a minimum of 3 people (more people are encouraged) when the cart is not appropriate. Students lifting ROV need closed-toes shoes or steel toed shoes if available. Lifting should be done with proper form and students involved should be confident in their ability and highly communicative with everyone involved in the moving process.

Hazardous Activity, Process, Condition, or Agent ROV Component Safety
Summary of Procedure or Tasks: The ROV will be transported on occasion between work spaces and testing locations and may need to be stored in small spaces.

Describe Hazards: ROV components, especially the thrusters, may be damaged during transportation/storage. Damage to the ROV could cause parts to fail and raise the risk of electrical shock when tested in water.
Hazard Control Measures: Components will be checked before working on or testing the ROV to ensure proper function. All components should have a "home" position in which they are protected by the outer skeleton of the ROV.

Disposal:

Hazardous Activity, Process, Condition, or Agent Li-ion Battery Disposal
Summary of Procedure or Tasks: ROV and mechatronic arm use Li-Ion batteries.
Describe Hazards: Lithium-ion batteries can retain charge even after the battery is damaged or appears to have died. It is critical to test the battery to ensure the voltage reads 0V.
Hazard Control Measures: Handle batteries carefully to mitigate risk of damaging the batteries. Dead or damaged batteries must be stored in the fire cabinet 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

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

Appendix E: Conference Presentation Slides

SANTA CLARA UNIVERSITY

Nautilus ROV Robot Manipulator

Dana Stefanides, Jenny Huynh, Andrew Stewart, Steven Reimer, Andrew Nguyen, Rebecca Walters, and Matthew Hayes

SANTA CLARA UNIVERSITY

Team Members & Partners

Mechanical Engineers

Andrew Stewart
Dana Stefanides
Rebecca Walters
Jenny Huynh
Steven Reimer
Andrew Nguyen

Computer Engineer

Matt Hayes

RSL

MBARI
Monterey Bay Aquarium Research Institute

Faculty Advisors

Christopher Kitts
Michael Neumann

2

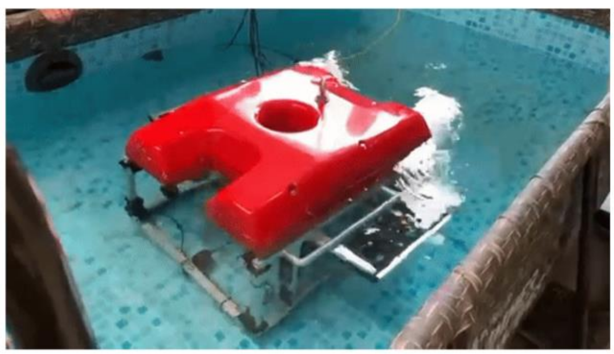
Motivations

3

SANTA CLARA UNIVERSITY

Underwater Robotics

The remotely operated vehicle, *Deep Discoverer*, being recovered after completing 19 dives during the Windows to the Deep 2019 expedition. *Image courtesy of Art Howard, Global Foundation for Ocean Exploration, Windows to the Deep 2019*



4

SANTA CLARA UNIVERSITY

Project Statement

Develop a novel prototype manipulator system for the Nautilus underwater robot.

5

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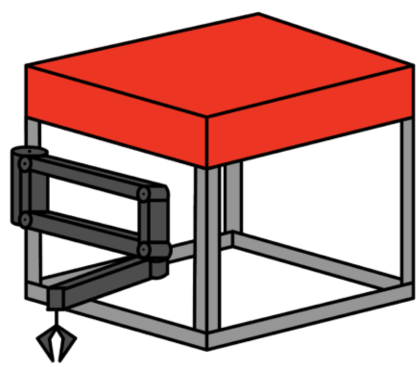
Agenda

- Background & Motivation
- Project Statement
- **System Overview**
- Soft Gripper
- Robot Arm
- Controls
- Integration & Performance



6

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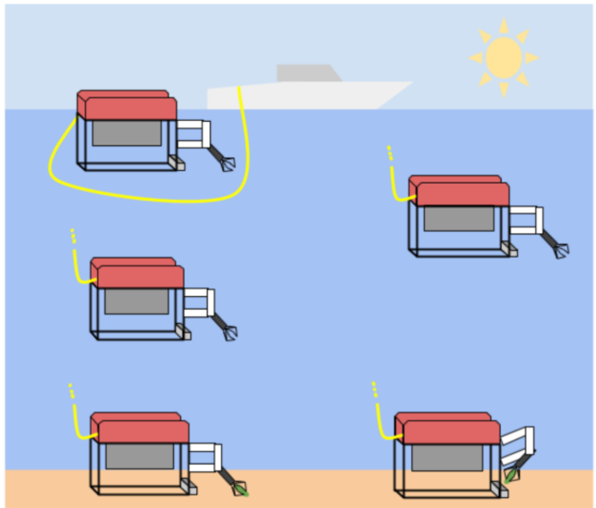
Concept of Operations

1. Nautilus is launched from a boat into the water.

2. Nautilus descends to the marine floor.

3. Manipulator arm grabs a sample.



5. Nautilus ascends to the surface.

4. Samples are placed in storage.

7

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Top-5 System Requirements

01	Sample Collection	Pick up and hold samples of unusual geometries between 3 and 8 in^3 without dropping.
02	Joint Control	Center the end effector directly above the sample ± 3 in. within 3 attempts.
03	Endpoint Control	Maneuver the end effector to a specific point in Cartesian coordinate space ± 3 in.
04	Sample Storage	Deposit the sample in the intended storage compartment with >90% success.
05	Workspace	Arm must utilize a working area >1.5 ft^2. Entire workspace and storage compartment must be visible through camera view.

8

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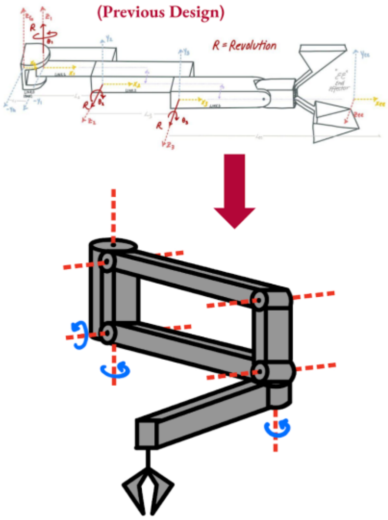
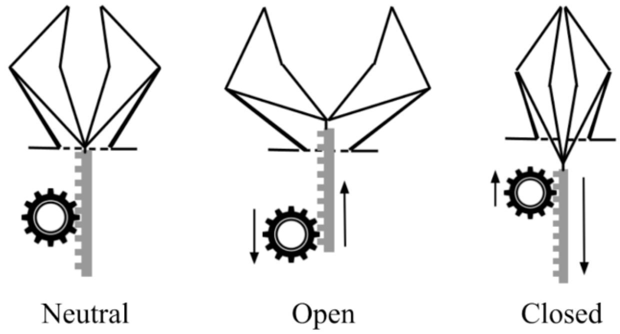
Mechanical Overview





9

SANTA CLARA UNIVERSITY

Agenda

- Background & Motivation
- Project Statement
- System Overview
- **Soft Gripper**
- Robot Arm
- Controls
- Integration & Performance

10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Soft-Gripping End Effector
Research and consult with experts in the field
Discussions of:
•Actuators
•Controls
Consider constraints:
•Budget
•Timeline
Purchase materials
Machine, laser cut, 3D print, epoxy, solder, and assemble individual parts
Research
Define Scope
Brainstorm
Model
Fabricate
Test
Specify measurable system reqs
Define Project Statement
Springs
Detailed models (CAD, Simulink)
Prototypes (Proof of Concept, Kinematic, Functional)
Design assays to measure system requirements
Test and adapt to challenges in real-time
Analyze test results
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Prototyping & Manufacturing
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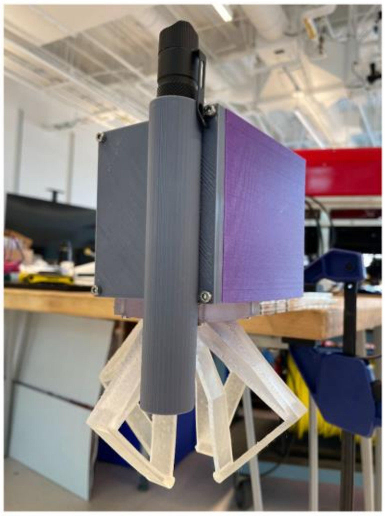
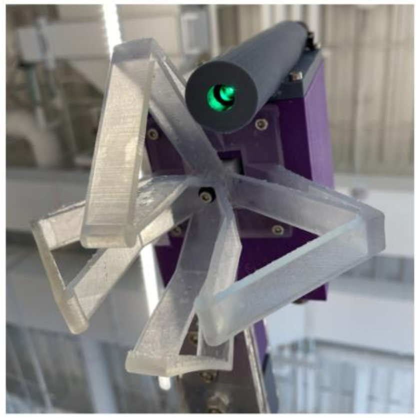
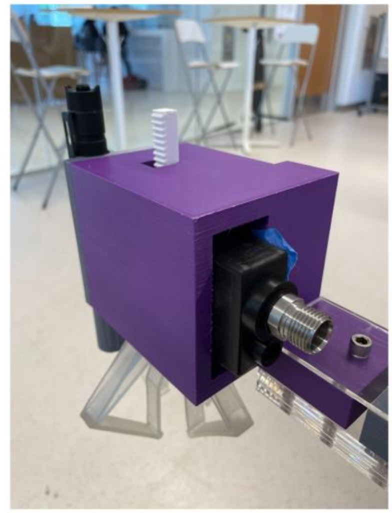
Final Design







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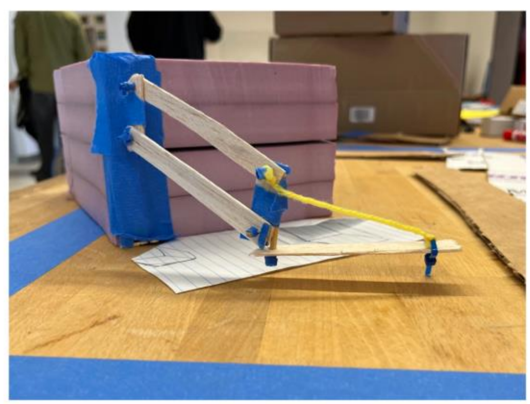
Agenda

- Background & Motivation
- Project Statement
- System Overview
- Soft Gripper
- **Robot Arm**
- Controls
- Integration & Performance



Notilus ROV

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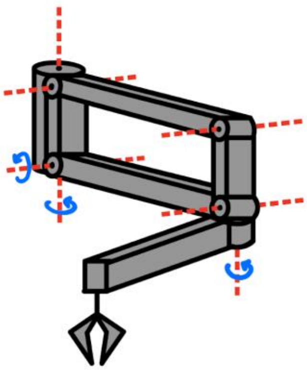
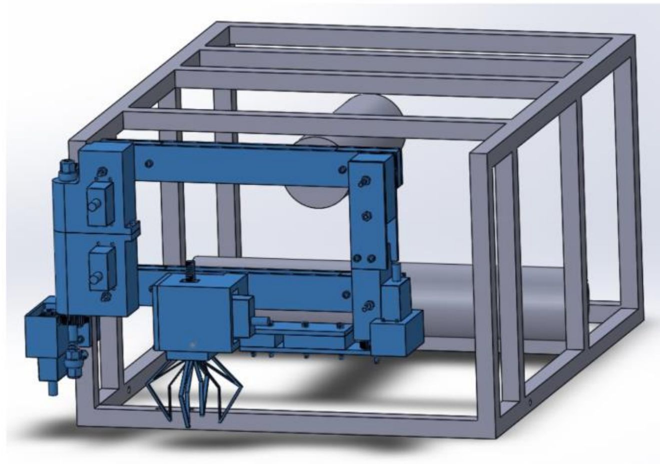
Robot Arm

- Parallel structure
- Uses 3 servos (designed to use 4)
- Added buoyancy foam





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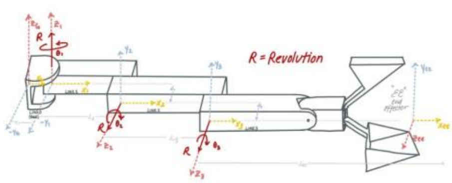
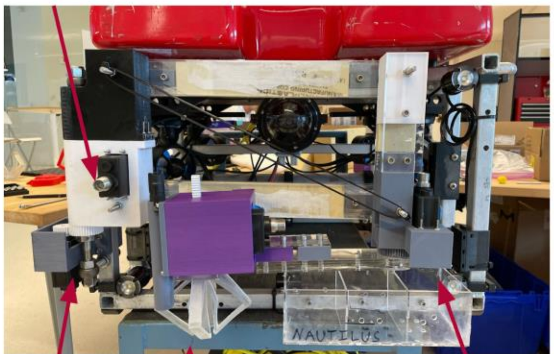
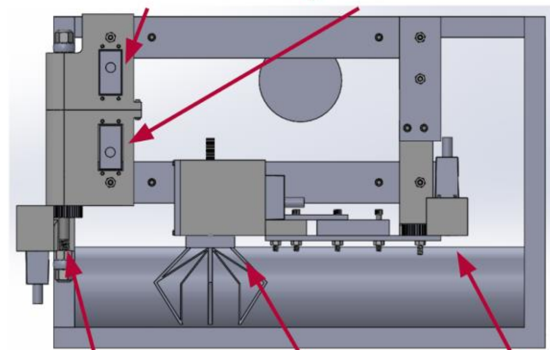
Arm Progression



Previous Team's Design

Final Design





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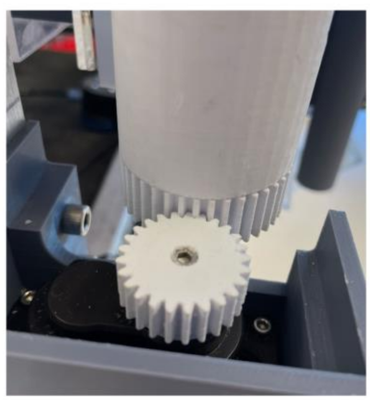
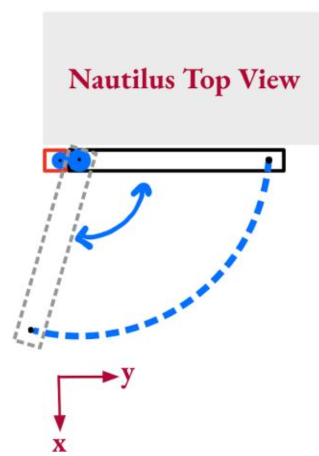
Joint #1





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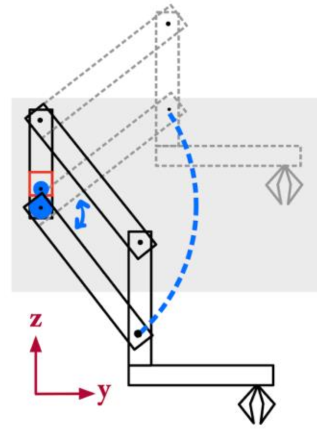
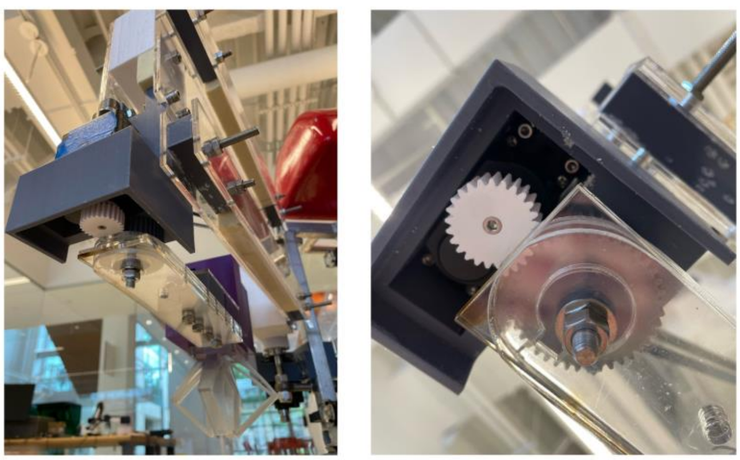
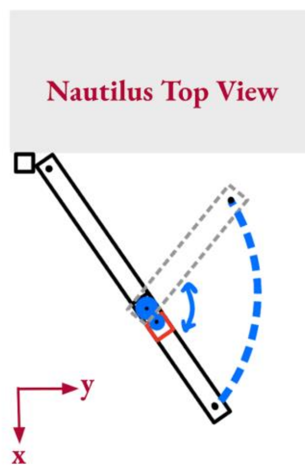
Joint #2



Nautilus Front View

Joint #3





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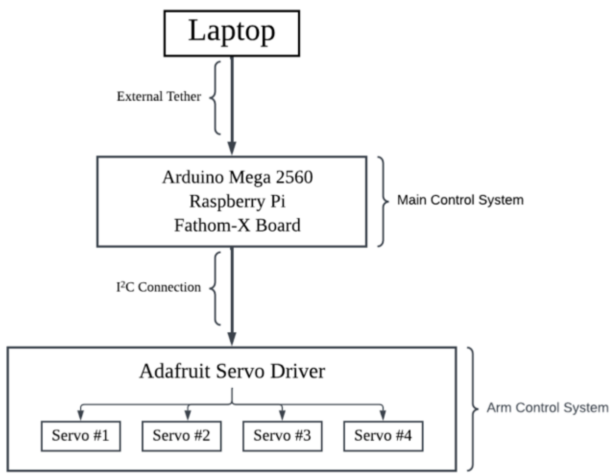
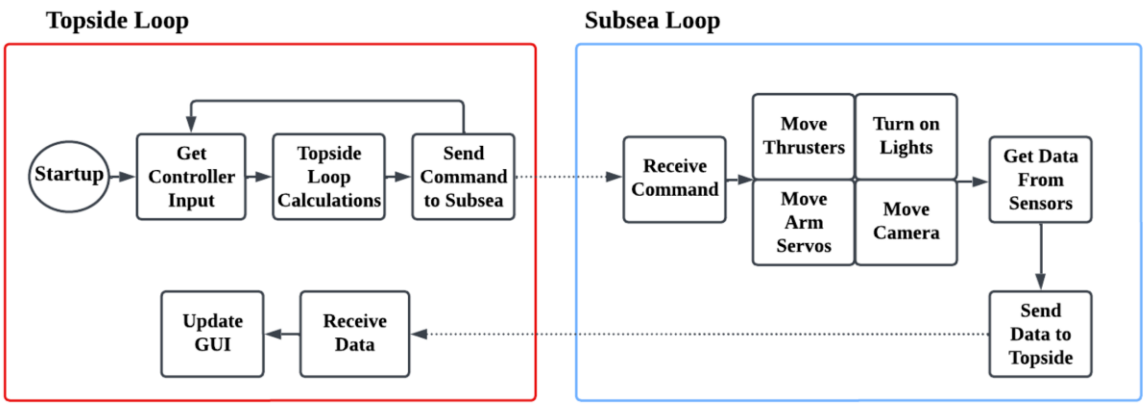
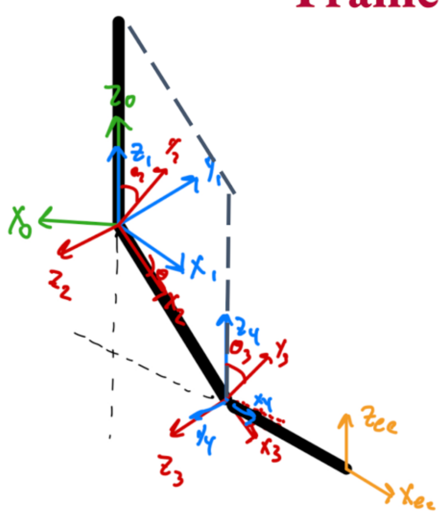
Component Block Diagram



High-level Software Processing



Frame Assignment



*Using 'modified Denavit-Hartenberg' method

DH Parameters	α	a	θ	d
1	0	0	θ_1	0
2	$\frac{-\pi}{2}$	0	θ_2	0
3	0	$L1$	θ_3	0
4	$\frac{\pi}{2}$	0	θ_4	0
ee	0	$L2$	0	0

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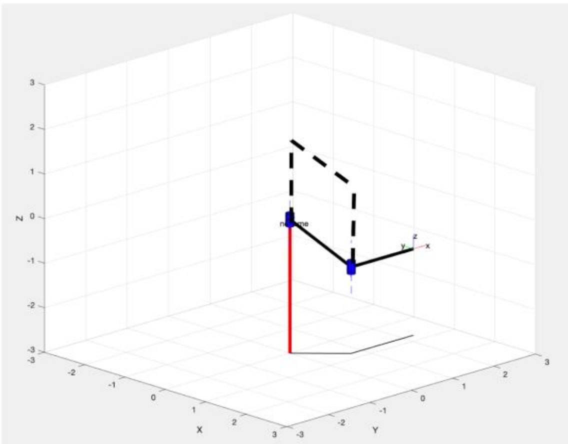
Robot Arm Model



$$ {}^{0}_{1}T = \begin{matrix} \cos(\theta_1) & \cos(\theta_1) & 0 & 0 \\ \cos(\theta_1) & \sin(\theta_1) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{matrix} $$

$$ X = \frac{L1}{2} cos(\theta_1 + \theta_2) + \frac{L1}{2}\cos(\theta_1 - \theta_2) + L2\sin(\theta_1 + \theta_4) $$

$$ Y = \frac{L1}{2} sin(\theta_1 + \theta_2) + \frac{L1}{2}\sin(\theta_1 - \theta_2) + L2\sin(\theta_1 + \theta_4) $$

$$ Z = -L1\sin(\theta_2) - L2\sin(\theta_2 + \theta_3)\cos(\theta_4) $$

$$ \dot{X}_{des} \rightarrow J^{-1}(\theta) \rightarrow Speed\ Calibration \rightarrow PWM\ Signal \rightarrow Servos $$

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Jacobian

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

$$ \frac{\partial x}{\partial \theta_1} = \frac{-L1}{2} sin(\theta_1 + \theta_2) - \frac{L1}{2}\sin(\theta_1 - \theta_2) - L2\sin(\theta_1 + \theta_4) $$

$$ \frac{\partial x}{\partial \theta_2} = \frac{-L1}{2} sin(\theta_1 + \theta_2) + \frac{L1}{2}\sin(\theta_1 - \theta_2) $$

$$ \frac{\partial x}{\partial \theta_4} = -L2\sin(\theta_1 + \theta_4) $$

$$ \frac{\partial y}{\partial \theta_1} = \frac{L1}{2} cos(\theta_1 + \theta_2) + \frac{L1}{2}\sin(\theta_1 - \theta_2) + L2\sin(\theta_1 + \theta_4) $$

$$ \frac{\partial y}{\partial \theta_2} = \frac{L1}{2} cos(\theta_1 + \theta_2) - \frac{L1}{2}\cos(\theta_1 - \theta_2) $$

$$ \frac{\partial y}{\partial \theta_4} = L2\cos(\theta_1 + \theta_4) $$

$$ \frac{\partial z}{\partial \theta_1} = 0 $$

$$ \frac{\partial z}{\partial \theta_2} = -L1\cos(\theta_1 + \theta_4) $$

$$ \frac{\partial z}{\partial \theta_4} = 0 $$

$$ J = \begin{bmatrix} \frac{\partial x}{\partial \theta_1} & \frac{\partial x}{\partial \theta_2} & \frac{\partial x}{\partial \theta_4} \\ \frac{\partial y}{\partial \theta_1} & \frac{\partial y}{\partial \theta_2} & \frac{\partial y}{\partial \theta_4} \\ \frac{\partial z}{\partial \theta_1} & \frac{\partial z}{\partial \theta_2} & \frac{\partial z}{\partial \theta_4} \end{bmatrix} $$

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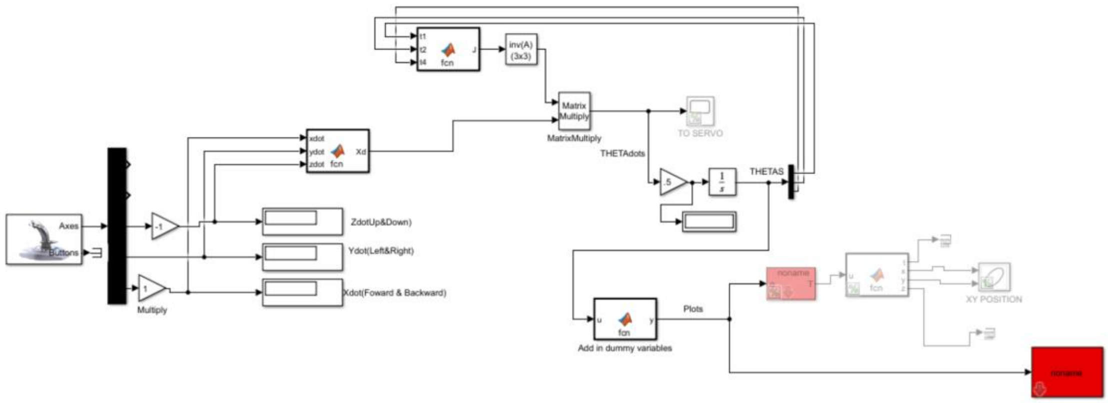
Cartesian Control Model



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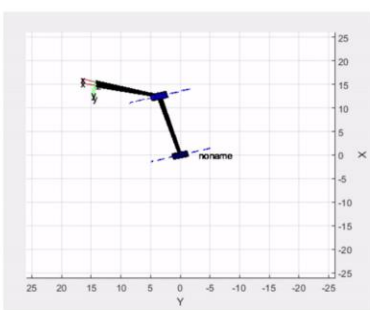
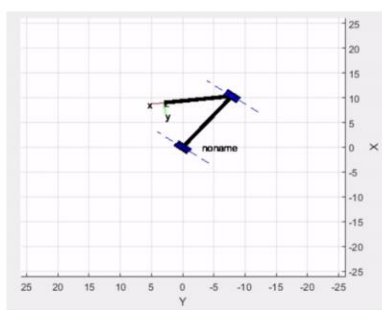
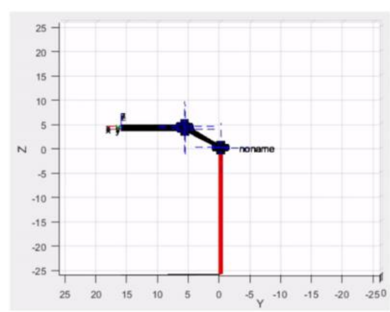
Cartesian Control Simulation



Cartesian Motion in X Direction



Cartesian Motion in Y Direction



Cartesian Motion in Z Direction

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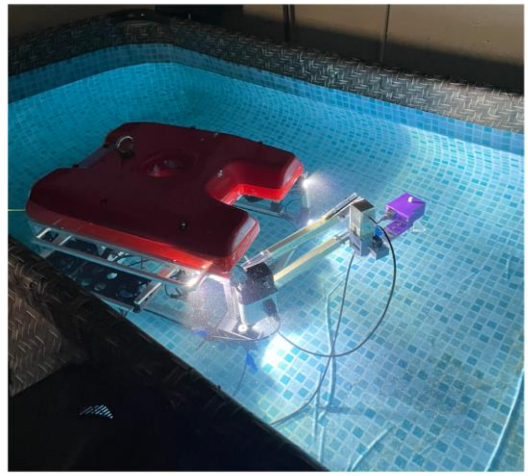

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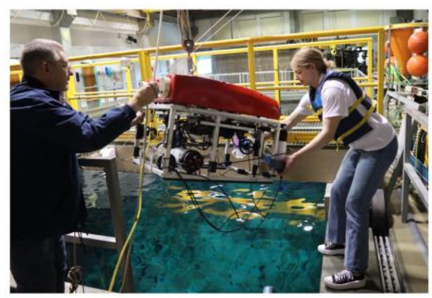
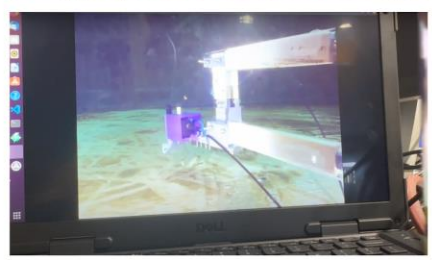
Testing





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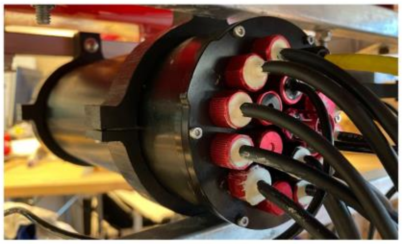
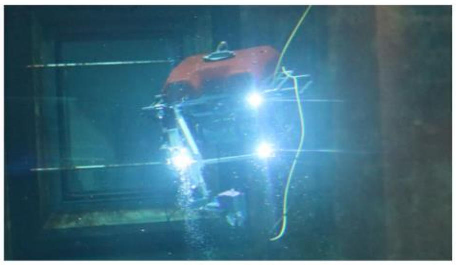
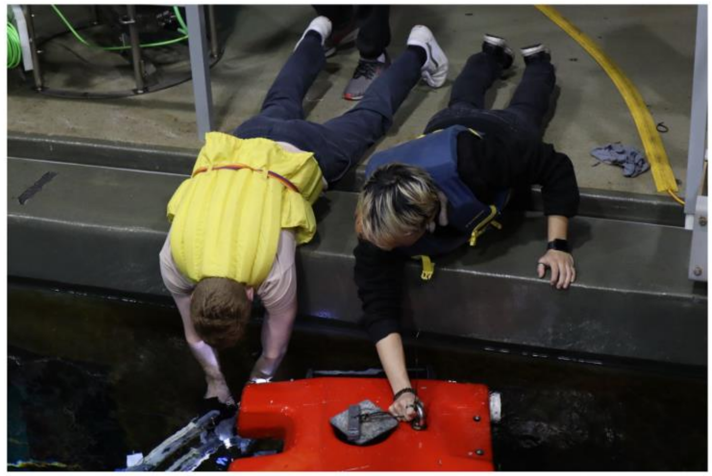
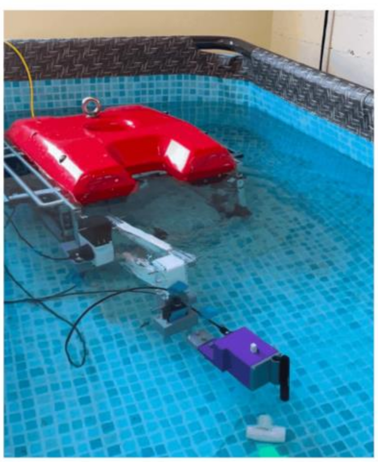
Challenges







Ranges of Motion



Joint #1

Joint #2

Joint #3

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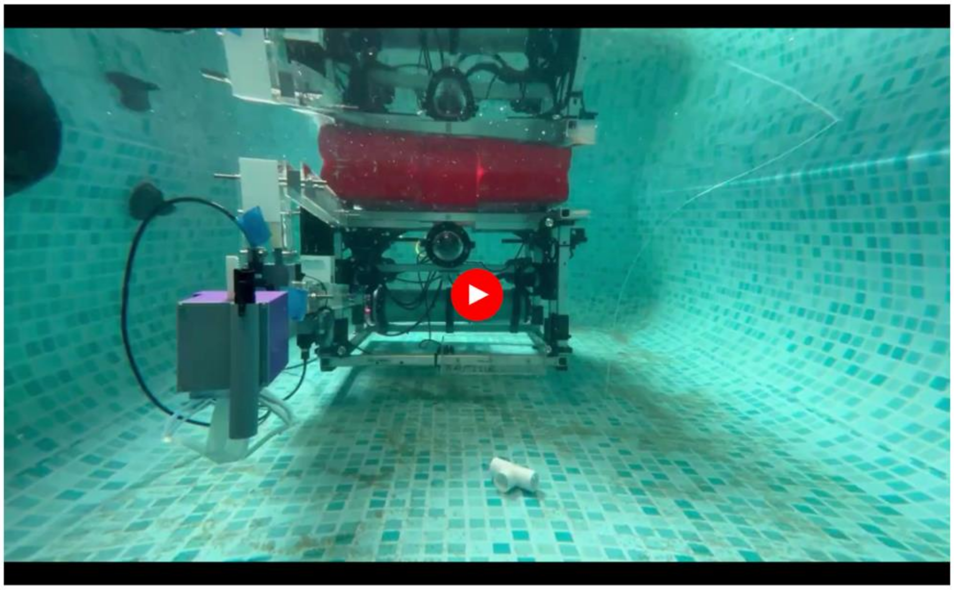

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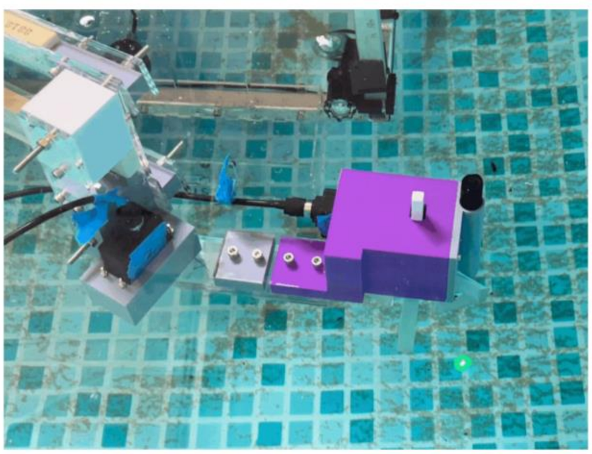
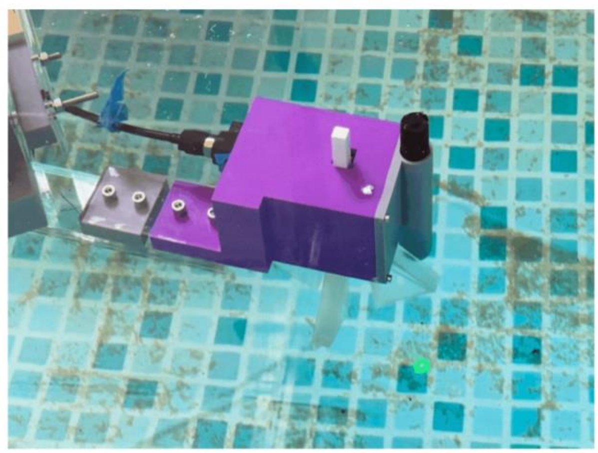
Cartesian Endpoint Control



X Motion



Y Motion

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10 Completed Tests

Average Time	2:30
Average Time	48s
Centering Attempts	1.8
Joint Range	130°
Joint Speed	1 rad/s
Gripper Cycle Test	500x
Grip Retention	100%
Buoyancy	Neutral

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System Evaluation

01	Sample Collection	Grab samples between 3 and 8 in^3	Successful grip of objects <6 inches across
02	Joint Control	Center End Effector above Sample in 3 attempts	Average attempts: 1.8
03	Endpoint Control	Functional Cartesian coordinate plane control system	Functional within a subset of the workspace
04	Sample Storage	Sample storage rate >90%	Storage rate: 95%
05	Workspace	Visible workspace >1.5 ft^2	Workspace: 2.5 ft^2

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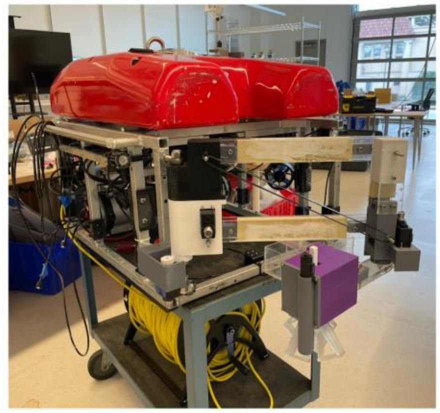
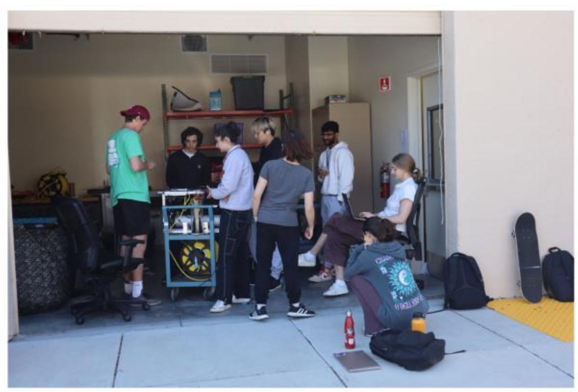
Phase I Summary

- Prototype manipulator system
- A soft gripper with:
  - 100% retention
  - 500+ cycles
  - Grasp objects of unconventional orientation
- Limited Cartesian endpoint control



Phase II Next Steps

- Address gear slippage and robustness
- Create a "sling" to manage the arm while Nautilus
- Integrate cable management system
- Fix the clear tube attachment
- Create organization for hardware inside
- Shorten camera delay (2 sec)
- Improve camera resolution



The Future of Nautilus

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Questions?

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