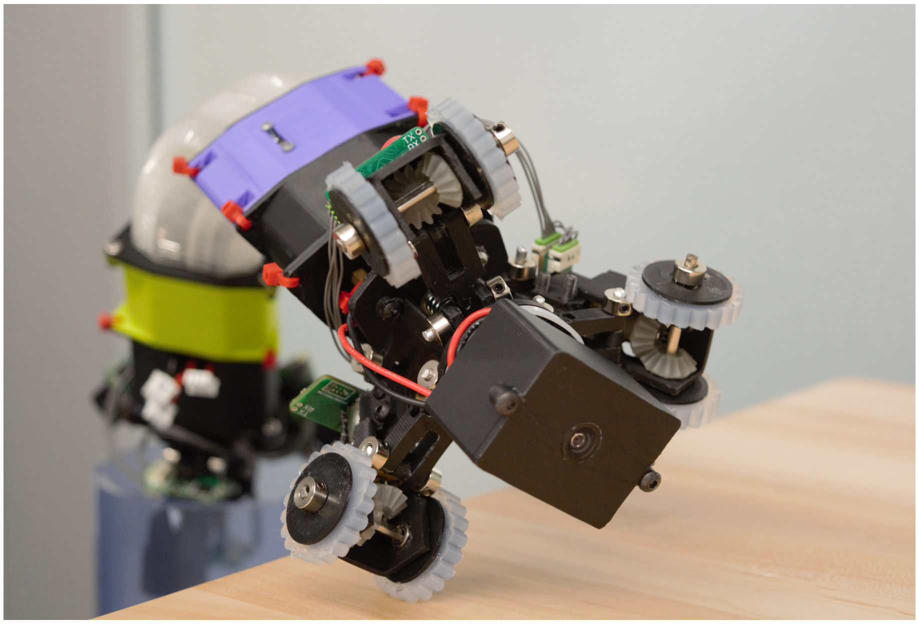
C.L.A.R.A. Pipe Network Exploration Robot
MQP 2023
Improvements in Robustness and Function



A Major Qualifying Project Report
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Abstract

This project follows in the footsteps of its predecessor project submitted in 2022 and aims to implement various mechanical and functional improvements in the robot. The previous year's project created a salamander-inspired soft robot for use in the inspection and exploration of pipe networks capable of maneuvering in a variety of pipe shapes, sizes, and configurations. The robot features an origami body segment of laser cut Dura-Lar (a hybrid of mylar and acetate) folded based on a Yoshimura crease pattern. This pattern allows the body segment to deform and bend in a manner controllable by three cable winch mechanisms, providing 3 degrees of freedom. The robot locomotion is achieved with a three-segment wheeled mechanism on a suspension-based linkage. These segments can expand and contract to provide variable force on the interior surface of the pipe, allowing for variable grip. This iteration of the project improved upon multiple systems of the robot to provide better functionality, robustness, and overall quality. New wheels were fabricated out of silicone for better grip. A new casing structure was introduced to improve rigidity and protection of vital robotic components, as well as reduce the overall robot profile. The new system uses an ESP32-Cam module to provide live footage to the operator. Relocation of actuators allowed for a maximum bending angle of approximately 150 degrees, an approximate 60% increase over previous iterations. This project expands upon the previous project's foundations, providing further support and functionality for future research and applications in pipe network exploration and inspection, and possible payload integration.

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1. Introduction

Intricate pipe systems are used for gas and water distribution, sewer and drainage systems and a number of other applications in which something needs to travel, often underground. These pipe networks require regular maintenance and inspection to ensure proper working order and the absence of damage like cracks, leaks, debris, etc. Humans are unable to explore many of these networks due to their length and land coverage, diameter, as well as health risks.

There are a number of present day technologies that can be used to inspect pipes of varying types to eliminate humans entering unsafe spaces. These technologies include borescopes, pole cameras, smoke and dye tests as well as sonar inspection. Some of these technologies are visualized through screens from a video stream whereas some allow one to determine whether there is a problem, but lack capabilities to visualize the actual condition or qualify the extent of the damage.

Borescopes in specific have a flexible tether so they can easily be navigated through the beds, curves and intersections of pipe networks. The probe tip has a camera and LED light to enable the viewing of conditions and provides a safe method for inspections in order to make determinations on damage and repair plans. Unfortunately, devices like borescopes are limited in their length, ease of maneuvering and lack many desirable features and capabilities. They are merely inspection devices and can provide no aid in repair of damages and are prone to breakage themselves. They also lack the ability to carry/release payloads, map out the geometry of networks, in addition to other sensing abilities and data collection; they mostly serve to provide a visual to the operator.

Modern day robots can serve the purpose of inspection, and are only limited by the length of their tether (if applicable) and the capacity of the on-board battery. This allows for an expansive range of exploration in addition to adding payloads or other aids to assist in inspection and repair. Consequently, an untethered system outfitted with sensors and payloads that can explore these networks opens numerous avenues for research.

2. Background

2.1 Previous Project State

The existing state of the CLARA Origami Exploration robot at the end of its first project year from 2021 to 2022 was the culmination of dedicated engineering work by our predecessors, Brian Katz and Kate Wheeler. The robot was a bio-inspired semi-rigid soft robot intended for the exploration of pipe networks, providing ease of inspection for a variety of pipe network types and sizes. CLARA is inspired by works like Salamanderbot and Ori-Snake, but proposes a smaller system capable of fitting various pipe sizes. The robot's key feature was a flexible origami body with wheels at both ends, one set of which was motorized to provide drive power. These wheel segments are able to extend and contract to provide force and gain traction to the inner surface of a pipe, as well as adjust for different pipe diameters. The flexible body allows the robot to bend and steer through any pipe junction, and is driven by three cable winch mechanisms which retract any one of the body segments three sides to provide the desired bending angle and direction. The motors are controlled by smart motor driver boards which receive signals from the main board through I2C. The main board of the robot receives commands via WiFi signal through an ESP32 microcontroller attached to a laptop and gamepad operated by the user.

However, the system as it existed was not without flaw, and upon receiving the robot from our predecessors, it was found to be non-functional due to necessary software updates, damage from tests, and time. This prompted us to begin an evaluation of its state, and use the information gathered to determine next steps.

2.2 Return to Functionality

Naturally, the first step of the project was to return the robot to functionality as it existed prior to the time period between the completion of the previous project and the beginning of ours. This involved investigation into the intended workings of the robot, as well as research into how the robot functioned in the first place. We followed diagrams, code, CAD models and additional resources from the previous team to comprehend the robot's abilities in addition to its shortfalls.

After charging the battery, investigating disconnected wires, and putting everything back into place, we were able to power the robot on. However, controlling the robot proved difficult, as the software created prior had become out of date, and updates to libraries and otherwise provided bottlenecks.

To return the code to working order, libraries were updated, and the code was modified to correct any syntax or library errors created by the updates. From there, communication between the gamepad controller and the laptop's serial ports was re-established by hard-setting the serial port designated for the controller to send button command signals to. This serial port would be connected to the ESP32 acting as the "sender," which sent command signals to the onboard TinyPICO which controlled the robot.

Upon finally fixing these issues and successfully sending commands from the gamepad to the robot, the robot motors began to move and demonstrate functionality. However, despite the success, mechanical problems began to reveal themselves immediately. Various hardware components, including nuts, bolts, bearings, shaft collars, and more began to fall off of the robot, and one or two 3D printed parts snapped. This prompted a full analysis of the mechanical function of the robot, its problems, and brainstorming of possible solutions and improvements that could be made to ensure the robot maintained functionality.

2.3 Problem Identification and Solution Brainstorming

Following thorough inspection and deconstruction of the system, we broke down our observations into categories for improvement and developed solutions for varying problems within each category.

2.3.1 Mechanical Robustness

As observed while returning the robot to functionality, many parts were loose, fit poorly, and installed incorrectly. Additionally, the awkward angles and jutting parts of certain essential robot components such as the winch modules and smart motor driver boards presented issues in our eyes. Should the robot encounter difficult geometry or other obstacles, it would be incredibly easy for a loose cable to become snagged and unplugged, rendering the motor it is attached to to stop functioning and strand the robot. Additionally, any mechanical parts jutting out at an odd angle could sustain physical damage requiring repair, also stranding the robot should it impact function. Following these observations, we wanted to ensure that this robot would be able to be taken out of the box and gotten to run again near immediately upon being picked up by another project group, should that be its fate. Additionally, we wanted to ensure that the robot could act as a reliable platform for research and development should future research groups decide to go in that direction. Therefore, mechanical robustness was determined to be a key problem which needed to be solved.

2.3.2 Origami Cable Wear

In the previous year's iteration of the CLARA robot, the winch motors and drums which drove the cables to contract the origami module were not inline with the channels of the origami itself. This meant that upon exiting the channel of holes in the origami module, a cable would take a sharp turn to get to its corresponding winch drum. This sharp angle meant that when driving these winch motors and drums, the cable generated a lot of friction on the origami, creating wear and eventually cutting through the plastic over time. Therefore, the long and time consuming process of laser cutting and folding a new origami module would have to occur every time the cable cut through. To save time and material, as well as further contribute to the overall robustness and quality of the robot as a platform, we decided this needed to be rectified.

2.3.3 Junction Maneuverability

Although the robot had previously been able to travel through junctions, the robot was only actively driven on one side, making it a challenging process. If the actively driven side could not maintain or gain adequate grip on the interior surface on the opposite side of the junction, it would not have enough force to overcome the compression of the passive side and pull the rest of the robot through.

Additionally, since the passive side was also constantly attempting to expand to its maximum size, the robot was unable to move backwards. If the robot encountered a sudden increase in pipe diameter, the passive end would quickly expand to a larger diameter, and backwards movement would become near impossible, as the driving force from the active end was not enough to compress the passive end through only the topology of the pipe. This meant that in certain scenarios, the robot could not move backward.

2.4 Further Improvements and Expansion Possibilities

In addition to the many mechanical fixes and improvements we wanted to make to the robot, we also had several ideas for general expansion. These were ideas intended not to rectify issues with the previous iteration, but to introduce functionality or applications not present on the previous iteration at all.

2.4.1 Camera Implementation

To serve its purpose as a pipe exploration robot, CLARA needed to be outfitted with sensors beyond the motor encoders in order to gather information and data. To begin this expansion, we decided to add a camera to provide visuals to the operator for navigation. This camera would provide the ability to make choices on direction at junctions in addition to being able to see pipe conditions. Additionally, we wanted this camera module to provide a live video feed to the operator of the robot, allowing them to make decisions as they were operating the robot about direction, pause, and general maneuvering.

2.4.2 Actively Limited Passive Suspension

The final system created by the previous team had a passive suspension on the passively driven end and an active suspension on the driven side. Looking at the active suspension, if it were to be compressed too much and lose grip on the pipe in any vertically slanted pipe, the robot would have no way to recover due to the free spin of the wheels on the passive end. Adding an actively limited passive suspension on each end allows the extension to be limited, ensuring the wheels don’t expand too much but also allowing them to be passively compressed as needed. Additionally, the suspension could be used to maintain grip on one end while compressing the other end for navigational purposes.

2.4.3 Wheel Types

The initial system possessed two wheel types that were matched to their purpose. On the passive end, stock 32 x 7mm wheels from Pololu were used as their main purpose was to just roll along while applying force to the inner wall of the pipe. These wheels functioned, but were not deformable and would need additional grip if actuated for effective locomotion. On the active side, custom wheels were designed with the following structure: a PLA center hub [7] to create an inflexible d-shaft hole for connection to the drive shaft, a TPU “tire” designed with compliance for deformation to pipe geometry, with a final overlay of silicone for additional grip. These tires were easily damaged, and required many steps for manufacture, increasing production time.

Figure 1: 2022 Custom TPU and Silicone wheel

Figure 2: Pololu 32mm wheel [2]

3. Project Strategy

3.1 Goals

As robotic systems all contain mechanical, electrical and software systems within, there is always opportunity for improvement in each, and updates in some systems consequently improve others, or require additional work to mesh together. Overall, we aimed to focus on mechanical improvements, which ultimately led to some electrical work, and software in order to implement new sensors and rearrange the structure of the system.

3.1.1 Mechanical Improvement

To provide a well-built, functioning robot, it was instrumental to identify points of weakness, areas for improvements and parts needing re-manufacture. Some parts and fasteners only required tightening or repositioning to return them to their initial state, but many were damaged, missing, or had poor functionality. Consequently, we knew we had to identify any parts or materials we would need to purchase in addition to those we needed to reprint in resin or PLA, or completely scrap and redesign from scratch.

One of the biggest weaknesses of the system was it being actively driven on only one side. This limited the capabilities of junction navigation in addition to overall mobility when trying to back up or provide additional locomotion in vertical orientations. Although we determined that making both sides active would increase the length of the system, we decided that the benefits outweigh the drawbacks and decided to replicate the driven side on the other end. Additionally, we wanted to improve the suspension design in order to limit the wheelbase diameter from extending while still letting it compress further. The initial robot had one passive and one active suspension, which meant that the active side could be extended or compressed to a specific diameter but could not compress or extend based on the pipes' geometry. Our next steps would include transforming the previous design into an actively limited passive suspension.

3.1.2 Electrical Improvements

The electrical improvements made to the robot for this project centered around the support of our mechanical changes. These included swapping the main battery out for a smaller battery pack to fit within our new casing, implementation of a camera, implementation of a main breaker, and a general overhaul of the wiring of the robot to increase robustness and quality of connections.

When we decided to reduce the overall body profile, we knew that the battery would pose an issue due to its size. At first, we considered simply turning it lengthwise to fit within the profile, but it was decided that this would add too much to the overall length of the robot for a single segment. Therefore, it was determined that a new battery pack had to be made out of smaller batteries wired together.

The camera module was a high priority task for this project, as it introduced essential functionality for the robots intended purpose. Wiring this camera would prove challenging, so power requirement was taken into account during the selection of a camera module.

The main breaker implementation was also a high priority task for this project, as previously the robot had no method of being powered on or off other than the unplugging or plugging in of the battery. Therefore, implementing a main breaker was deemed all but necessary for the project to become an established platform for testing and research.

Finally, upon inspection of the robot following its return to functionality, a number of less-than-ideal wire connections were discovered, including that of the power wires to the mainboard. Additionally, as the battery was to be replaced by a series of smaller battery packs, these would need to be wired together too. To this end, a complete overhaul and rewiring of the essential robot components was in order to ensure quality connections and proper insulation between wires in close quarters to prevent shorts.

3.1.3 Software Changes / Analysis

Following the software changes made to the CLARA robot and its codebase to return it to functionality, there were few changes intended to be made to the software directly. However, we knew that there would need to be changes made to the code pending the implementation of new systems and modules which introduced new motors. To facilitate this, a thorough analysis of the established code of the robot was performed to gain an understanding of its general functionality.

Overall, the codebase of the robot consisted of three main sections: The master code to be uploaded to the onboard TinyPICO, the sender code to be uploaded to the sender ESP32-Dev board connected to the operator laptop, and the python interpreter code run on the operator laptop to translate inputs from the gamepad to the serial communications to the sender ESP32.

The master code file, *pico_master_2023.ino*, is built up of several functions designed to send the correct control signals to the I2C network established between the various motors on the robot. On startup, the TinyPICO main board establishes I2C communication with the connected motors, asserts itself as a WiFi station, and connects to the sender ESP32 through its mac address. Upon receiving a command from the sender ESP32, the various functions send the desired command data through the I2C network to the corresponding motor for the desired function.

The sender code file, *pico_sender.ino*, is built similarly to the master code file. On startup, it establishes itself as a WiFi station, connecting to the master TinyPICO through its mac address. It then begins listening for serial communication on its connected port. Upon receiving serial input on this port, the data is interpreted to determine the desired control, and the corresponding command data is sent over WiFi to the mainboard TinyPICO.

The python interpreter is a fairly simple python script which identifies HID, or human interface devices, to find the connected gamepad. Then, it listens for gamepad input, and assembles the data of currently activated buttons into simple bit format, sending that data to the serial port specified in the *config.yaml* file.

The only new code file introduced in the 2023 iteration of the CLARA robot code base is the *ESP32-CAM-Code.ino* file, uploaded to the ESP32-Cam module. This code is a modification of the Espressif *CameraWebServer* example code file. This code hosts a web server on the local network and streams the video captured by the ESP32-Cam live to the web server. However, this code was modified such that the ESP32-Cam module acts as its own WiFi access point rather than connecting to the local network. This bypasses issues with connecting to networks with password protection, or business networks which require security keys or otherwise. Instead, the operator laptop can be connected to the network hosted by the ESP32-Cam, and the live video feed can be accessed through a browser by entering the local IP address of the camera module, 192.168.4.1, into a browser window.

3.1.4 Performance Improvements

In terms of overall performance, there were a number of areas we wanted to improve. In terms of locomotion and navigation, we focused on developing a mechanically sound system for overall function. This involved reconsidering the suspension and winch design, in addition to printing parts in different materials or editing their form for increased robustness. We also discovered the need for dual-drive for easier navigation backwards, vertically and through junctions.

3.2 Objectives

Following the analysis of the shortfalls of the previous iteration, as well as the determination of the project direction, specific goals were identified which would act as key milestones and improvements to the robot.

3.2.1 Casing Redesign

Though the previous system was shorter than the updated design, a significant number of the main electronic components for controls and actuation were completely exposed, leaving them prone to damage from impact, liquids, dirt and debris. To ensure a robust system that is resistant to damage, we aimed to create a standard profile to house all exposed components excluding the motors and their smart driver boards. We wanted to redesign the mechanical structure by basing our footprint off of the origami profile, and created individual casing segments and re-oriented/re-designed parts to fit within these standard casing pieces. This also involved replacement/reorientation of the battery as it was encased, but was bulky and protruded far outside the profile.

Future work will focus on waterproofing to ensure no water damage to the robot during exploration missions, and the casing redesign is a significant initial step towards waterproofing, as parts must be contained with watertight seals. By creating a standard casing design, it enables easier reorganization and replacement of modules in future work. Additionally, the casings could be accompanied by rubber stoppers, o-rings and the like to provide a watertight seal for initial iterations. Standardization increases the efficiency of additions by reducing the need for design of custom parts to fit each individual need, but rather find a solution that is beneficial to the system as a whole.

3.2.2 Motor End Duplication

The given system possessed only one actuated wheelbase for locomotion. In order to improve its ability to navigate junctions, go backwards or vertically, we determined that it would make sense to duplicate the motorized end on the other side. In addition to this, the active side had an active suspension, meaning that the wheels could be moved to a specified wheel base diameter, but are unable to exert force to a pipe without the operator actively extending or compressing the wheels. To address this, we wanted to create an actively limited passive suspension. This would allow the operator to choose the max wheelbase diameter that they desire, but the wheels can still compress inwards, as they are spring loaded and can passively apply force when entering smaller pipes. This also prevents issues of immediately losing grip if a pipe becomes wider or a junction is encountered. Junction navigation is made easier as the robot can passively keep traction on at least one end of the robot as the other half navigates through. In the previous iteration, the use of a passive end meant that it could fully expand in junctions, impeding its locomotion as it tries to pull the wheelbase into the straight pipe and compress it.

Furthermore, creating an “all wheel drive” system means that the robot has stronger capabilities in navigating over uneven terrain and debris in addition to increasing overall traction. When traveling vertically, the previous iteration would slide down the pipe in the case of the actively driven side losing traction. With a dual driven system, the likelihood of losing traction and dropping down a pipe decreases. The robot also attains capabilities to easily use a T junction to turn around and flip its orientation for camera vision as each end can be driven in and out of the junctions.

3.2.3 Sensor Implementation

As an exploration robot, the system requires sensors to gain feedback and consequently react to its environment. The only existing sensors were the encoders on the smart driver board, but there were no sensors for vision, data collection, mapping, etc. which are all essential functions of the robot. As seen on KANTARO [14], pipe exploration robots can use sensors such as laser scanners, cameras, and inclination sensors to gain information about the environment. Laser scanners, or LiDAR can be used to collect scans of pipe geometry, and create maps using Simultaneous Localization and Mapping [4]. These maps can be utilized for future work in improving the autonomy of the system, and creating pre-set exploration routes. Additionally, the implementation of an Inertial Measurement Unit (IMU) would allow the operator to know the orientation of the robot and navigate accordingly.

The implementation of additional sensors will also enable simpler, more efficient navigation through pipes due to the inclusion of “vision” using a camera or other sensors that can assist in mapping terrain. Including a camera enables the operator to let the robot out of sight as long as it is within range, extending the area which can be explored. Additionally, it enables the user to see and evaluate pipe conditions in real-time.

3.3 Design Specifications (proposal)

The development of our project occurred under the following specifications:

1) All materials, parts and miscellaneous items bought for the project will not exceed $500.
2) The robot's profile will be such that all sections excluding the motorized wheel bases fall within the outline of the origami body.
3) Casings will enclose all electrical components excluding the smart motor drivers and attached motors.
4) The winch cable system will be redesigned to align the winch coil with the origami holes to avoid damage caused by friction.
5) Wheel materials and designs will be explored to determine ideal characteristics for maximum grip, force and friction to pipe walls.
6) A camera will be attached to the robot and powered to enable live video feed for visual feedback of pipe conditions.
7) The passive end of the first iteration will be actively driven and possess an actively passive suspension.
8) The origami body will be replaced with a newly folded module.

3.4 Timeline and Approach

To facilitate the completion of the intended project goals, general project milestones were determined with preliminary deadlines of completion. These milestones and deadlines were compiled into a gantt chart spanning the course of the year. This schedule, while it served as a good guide to generally keep us on track, was not entirely abided by, as it was created prior to the extension of the project into D term. That being said, the following shows the list of milestones and their initial intended deadlines. Additionally, some of the milestones were abandoned throughout the project, as they were deemed “reach” milestones,and ended up being out of scope for this year's iteration of the project.

Milestone	Start Date	End Date
Determine Project Direction	8/24/22	9/27/22
Return Existing Robot to Functionality	9/27/22	10/22/22
Improve Casing Structure	11/7/22	11/20/22

Casing Testing	11/7/22	11/20/22
Redesign Flex Body Winch Module	11/7/22	11/20/22
Explore Wheel Types	11/21/22	12/4/22
Motorize Wheels	11/21/22	12/11/22
Develop Active-Limited Passive Suspension	11/21/22	12/11/22
Implement Camera	11/28/22	12/18/22
Develop Camera GUI / Code	11/28/22	12/18/22
Develop Module Connection Format	1/9/23	1/29/23
Test Connection Strength	1/16/23	1/29/23
Test Electrical Signal / Throughput	1/16/23	1/29/23
Top Modules	1/30/23	2/19/23
Final Paper	2/13/23	2/31/23
Final Presentation	2/13/23	2/31/23

Table 1: Initial project milestone development dates

3.4.1 Part Replacement and Manufacturing

In the first few weeks of our project, we dedicated time towards doing a complete inspection and disassembly of the robot in order to determine parts that were missing or broken and needed to be replaced, and parts that we wanted to iterate and improve upon. During this time, we identified numerous drive gears and motor shrouds that were cracked, unfastened or poorly manufactured. For FDM printing we purchased Ultimaker Tough Black PLA for use in the Ultimaker S7. Additionally, we used the Form3L SLA printer and Tough 1500 V1 resin [8] found within the lab to aid in reprinting these essential parts and providing a thin layer height for smooth, precise printing. Additionally, we spent time developing and testing ideal printing and processing conditions to produce quality parts that would increase the structural integrity of the robot. We utilized the SLA printer to reprint the FDM gears as the non-smooth surface created by FDM printing adds friction and vibrations to the system, degrading and loosening key parts.

3.4.2 Mechanical Design Process

For all designs including new or edited, we utilized Solidworks and Onshape for modeling, Formlabs PreForm and UltiMaker Cura for slicing, and the Form3L, UltiMaker S5 and Ender3 printers for part production. The SLA printing process also included agitation in TPM solvent using the Form Wash+ and curing in the Form Cure +. This system allowed us to easily access and work on all designs, save print settings and track the status of prints. Our mechanical design often needed a minimum of 3 iterations to perfect tolerancing, print quality and perform fittings and tests. Though there were a large number of mechanical improvements we intended on making, ideas and designs were often developed simultaneously for individual systems as they had interconnections that required careful thought. This approach was quite beneficial as it minimized additional redesigns due to module mismatch. This led to many systems being finalized and fully connected to the entire robot in the 3rd quarter of our project, but we were able to perform tests prior as other parts were being completed.

3.4.3 Electrical Design Process

Electrical design was less of a planned out process due to the nature of the ever-changing mechanical modifications. General wiring choices were made initially, but the real-world physical structure of the wiring harness changed multiple times over the course of the project.

In general, certain decisions were made with regard to modifications of the wiring and electrical design of the robot. These include the implementation of a 5V regulator to provide power to the camera, a main breaker's insertion between the battery pack and the main load sources, and the shifting of the power source requiring multiple battery packs to be wired in parallel.

Electrical wiring diagrams were made simply for demonstration purposes in MATLAB simscape architecture, rather than a true electrical schematic software due to availability and knowledge of software usage.

3.4.4 Testing and Analysis

Following the determination of project goals toward the beginning of the project, certain tests and metrics were chosen to allow for proper analysis of the robot improvements. These included physical performance metrics, as well as more abstract metrics with regard to software, controllability, and more.

Some of the metrics chosen included payload weight, bending angle, junction maneuverability, movement speed, and more. Unfortunately, we experienced several setbacks over the course of this project which limited the amount of testing we were able to complete following the completion of mechanical, electrical, and software changes.

4. Design

4.1 Casing Improvements

To contribute to the overall project goal of increased robustness and protection of essential components, a new casing was designed for the robot's main segments. Each casing section was designed and iterated upon to maintain functionality and fit within a consistent body profile.

4.1.1 Body Profile

The design of the new body profile was generated based around the shape of the main board of the robot. The profile consists of a semi-rounded triangular shape with an inner and outer profile. The inner profile is the shape of the main board projected and expanded 3 mm outward. The outer profile is the same shape projected again and expanded another 2 mm. In addition to expanding 2 mm, the corners of the semi-triangular shape were extended to provide expansion toward the vertices, allowing extra space for the inclusion of three 3.5 mm diameter holes. These three holes at the vertices provide clearance holes for M2 hardware, and provide a consistent location for connection hardware between segments utilizing this profile. In the center of the new profile is a 1.5 cm diameter hole. This hole acts as a minimum opening for feedthrough of power and signal wires. In some segments, this hole is of varying shape or size, but this 1.5 cm diameter was chosen as a minimum to ensure that essential power and signal wires are able to pass through the entire central length of the robot.

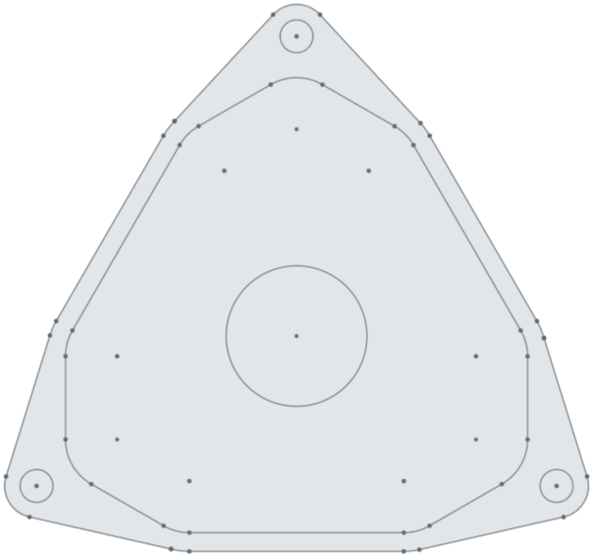


Figure 3: Top-down view of new body profile essential sketch

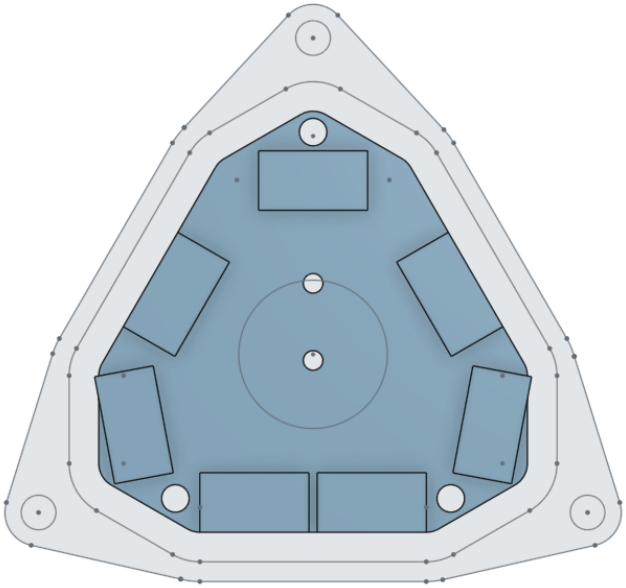


Figure 4: Top-down view of new body profile essential sketch with overlaid main board model

4.1.2 Main Board Casing

The first casing designed using the aforementioned body profile was the main board protective casing. The main board of the robot consists of a custom PCB, a TinyPICO ESP32 Development Board, and a 12V step down regulator which provides power to the N20 Motors throughout the robot. To help these components fit within the new profile, the 12V step down regulator was reoriented from horizontal to a vertical orientation.

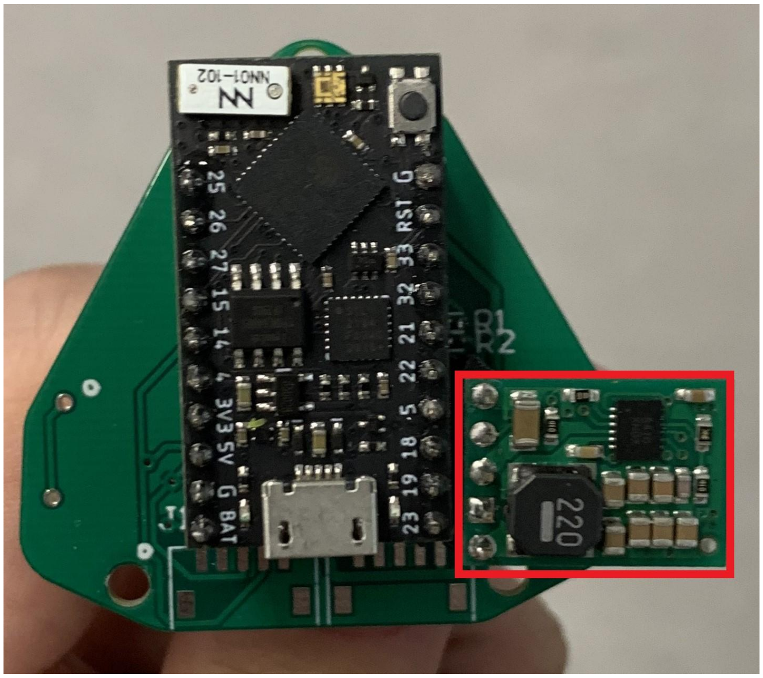


Figure 5: The main board of the CLARA robot prior to rotation of the 12V step down regulator (highlighted in red)

The general design of the casing is 2 mm thick vertical walls following the 9-sided rounded triangular profile of the main body at an offset distance of 3 millimeters from the sides of the main board. At the top and bottom of the casing following extrusion are two flat plates which follow the extended more triangular profile to feature the mounting holes. In addition, the bottom surface of this casing is a 2 mm thick plate featuring the 1.5 cm diameter hole to allow the passage of power and signal wires. However, the top surface of the casing was left more open to allow for the installation of components; a pattern which would be repeated in further casing segments. On the inner surface of the bottom plate, three small pegs were designed in to allow for alignment of the main board, as these pegs fit neatly through the 3 mounting holes of the main board. Finally, a small 2 cm wide by 1 cm tall rectangular hole was cut out of the side of the casing to allow for the connection of USB cables to the main board allowing programming and testing of the TinyPICO.

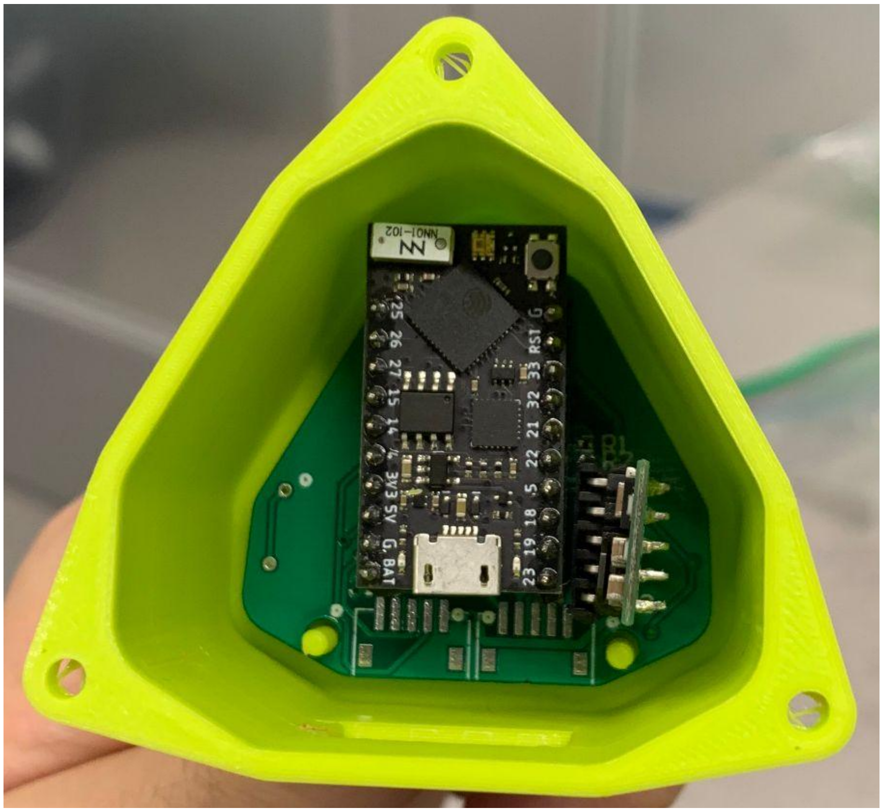


Figure 6: The main board within the new casing without wires; Top View with the 12V step down regulator reoriented

Figure 7: The main board within the new casing without wires; Side View through the rectangular access port for USB connection

4.1.3 Battery Housing

Prior to the implementation of the new casing and body profile, the battery and its housing were one of the largest components of the robot overall. To fit within the new profile, the large and cumbersome battery was replaced with a series of smaller batteries, which is detailed in Section 4.5.1. In designing a housing for these batteries, several factors were taken into account, including charging, protection, and the implementation of the new main breaker, detailed in Section 4.5.2.

The first iteration of the battery holder with these new batteries in mind featured the same main design as the main board holder. The main body followed the semi-triangular profile in the vertical walls with flat plates on the top and bottom for mounting holes. The key distinguishing features in this segment, however, were the rectangular cutout on one edge of the side wall for the main power switch, and the larger cutout on the opposite flat side wall for the batteries themselves.

The rectangular cutout for the main power switch was 3.2 cm tall by 1.4 cm wide, and placed on the rounded edge of the side wall to reduce the amount of wasted space on the interior of the housing.

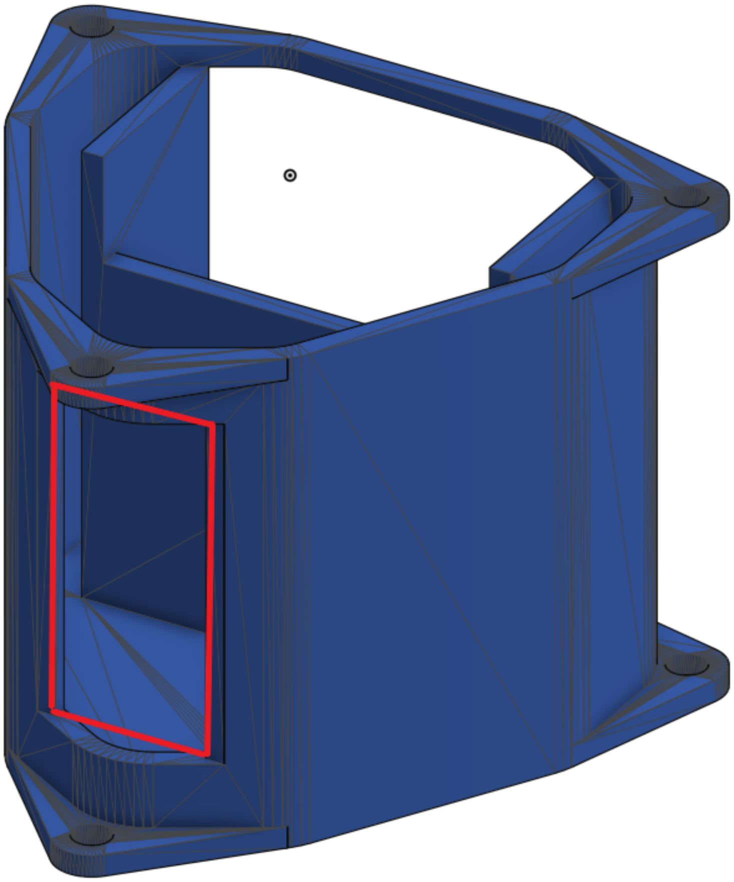


Figure 8: First battery housing iteration with main breaker cutout highlighted in red

The larger cutout on the opposite side of the housing was a 3.6 cm wide by 4.2 cm tall cutout meant for the insertion and removal of the battery pack itself. Additionally, 3 vertical walls were placed on the interior of the housing to retain the batteries and separate them from the wiring in the rest of the housing.

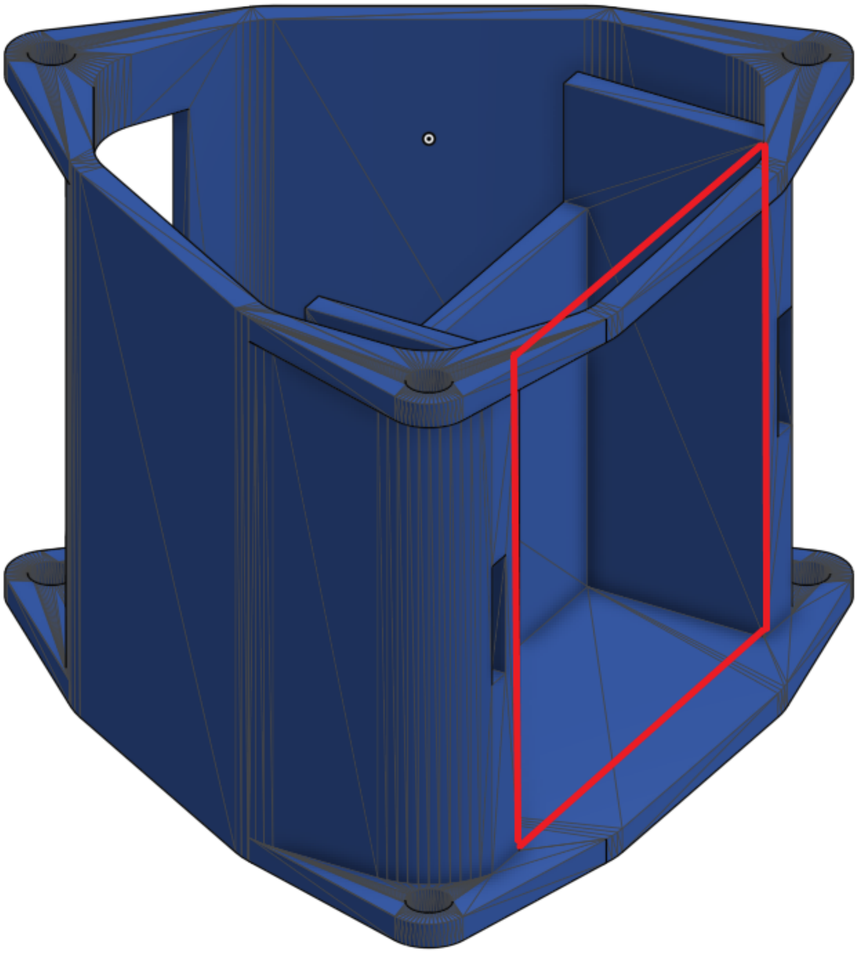


Figure 9: First battery housing iteration with battery insertion cutout highlighted in red

Finally, on either side of the main battery cutout were two 1 cm by 2 mm slots intended to receive 'clips' which would be located on the cap of the battery housing. This cap would retain the batteries inside the housing, protecting them from external damage and preventing them from falling out.

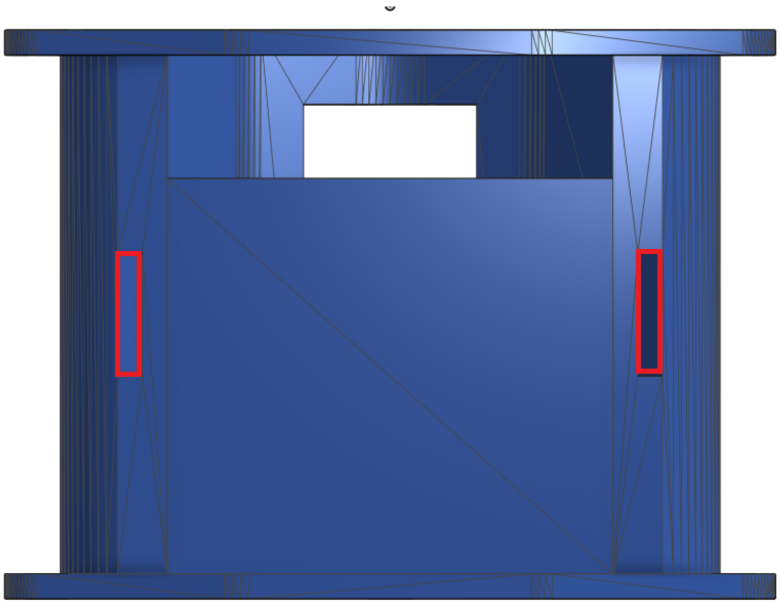


Figure 10: First battery housing iteration with battery cover clip slots highlighted in red

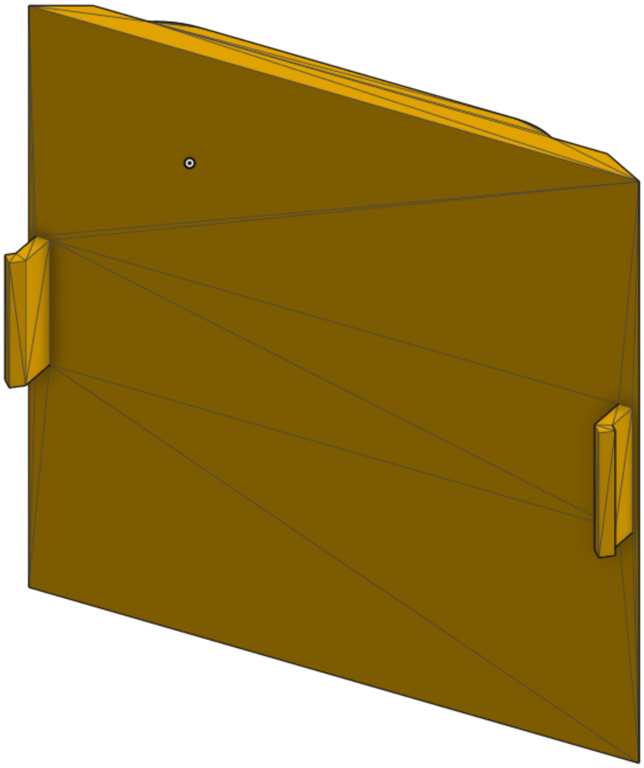


Figure 11: First battery housing iteration retention cap

This design, however, was not the final design, as it had several issues. The first issue was the cap. The cap designed to clip into the housing and retain the batteries was able to be inserted easily, but removal was difficult and awkward. Often, removing the cap would damage the clips, resulting in the necessity of replacement of the cap. Secondly, the vertical retaining walls on the interior of the housing did serve their intended purpose of separating the batteries from the wiring. However, they took up too much space and were deemed larger than necessary to serve the purpose they were designed for. To fix these issues, the second and final iteration of the battery housing was designed for these new batteries.

In the new iteration, the large rectangular cutout for the insertion of batteries was replaced by a smaller 1.5 cm wide by 7.5 mm tall cutout not intended for the removal of batteries, but simply to allow the charging cables of the batteries to be accessed. The decision was made to not allow the batteries to be easily removed from the robot, but instead to be installed into the robot when the entire segment itself was installed, and simply have the batteries be charged while inside the robot. Since a main breaker was implemented (see Section 4.5.2), we determined that the batteries could be safely charged while inside and connected to the robot without damaging other components so long as the main breaker was shut off.

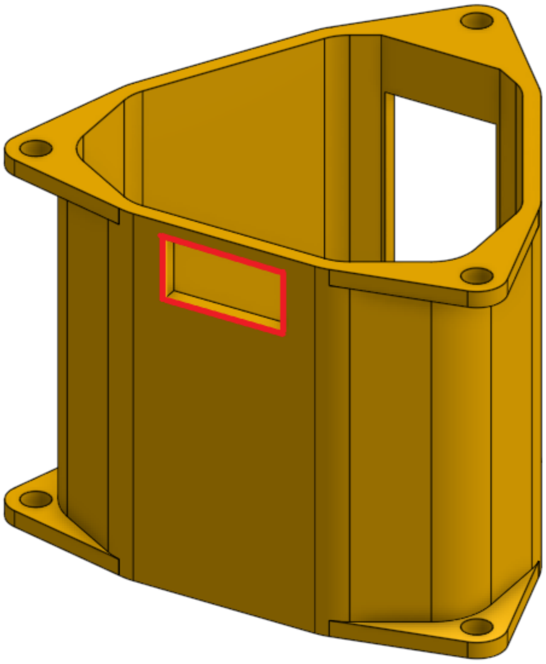


Figure 12: The final iteration of the battery holder with the smaller charging cable access cutout highlighted in red

In addition, the retaining walls on the interior of the housing were shortened to only 5 mm tall. This new height allowed them to still serve a purpose of keeping the batteries in place, but did not provide any issues with regards to space for wires or other components.

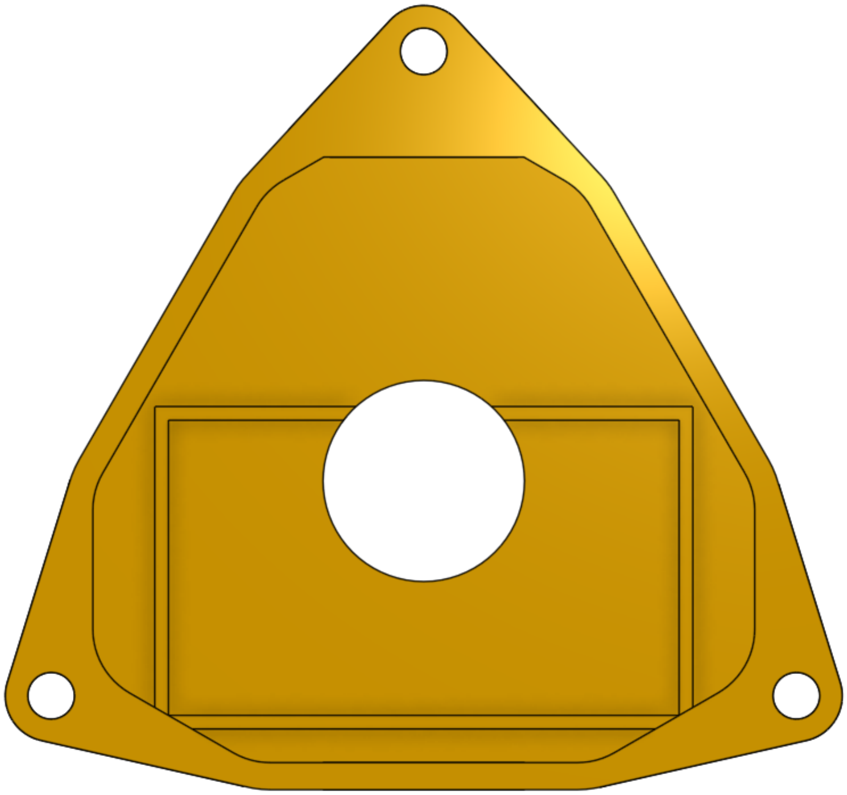


Figure 13: Top-down view of the final battery housing iteration

The rectangular cutout on the vertex opposite the battery charging cable cutout was left the same, as it did not present any issues from the first iteration.

4.1.4 Winch Housing

To protect and support the new winch module developed for this iteration of the robot and detailed in section 4.3, a new housing was developed for the module. The general design of this module followed the same principles as all the previous new housings with regard to the main vertical walls, as well as the mounting plates on the top and bottom. To support the new motor orientation detailed in section 4.3.1, a ~2 cm long round slot with a 2.5 mm diameter / width was cut in each side wall for attachment of the two bolts which held in the motors through the white plastic mounting brackets.

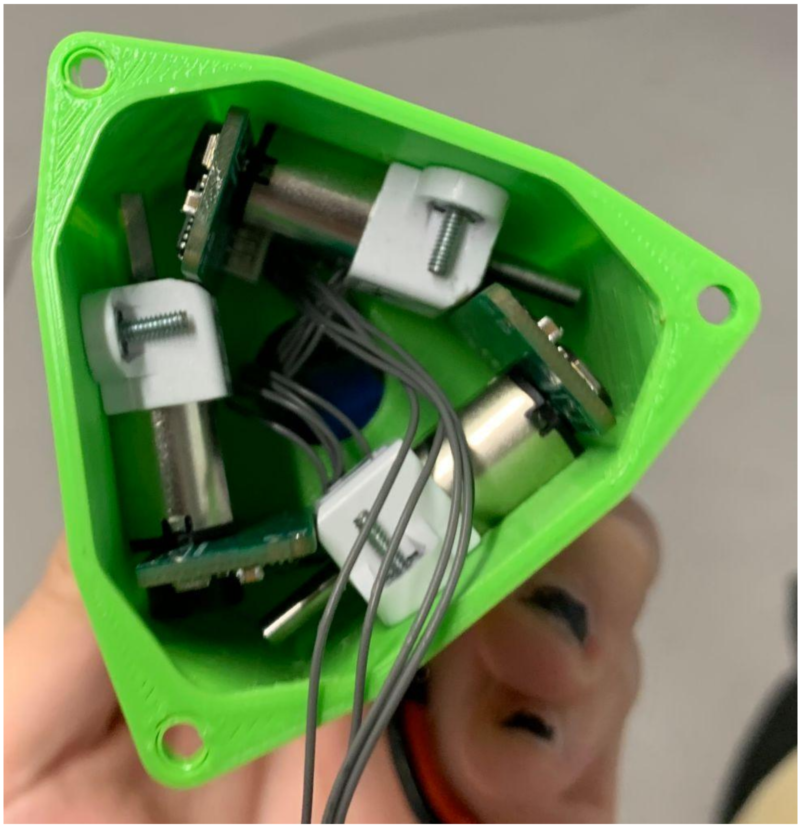


Figure 14: Top-down view of the new winch module housing first iteration with motors installed in their new orientation

After printing, assembly, wiring, and testing of this first iteration problems were encountered with the functioning of the motors themselves. After diagnosis, this was determined to be due to the very constrictive tolerances of the new housing providing not quite enough room for the motors and winch drums in their entirety. More specifically, the magnetic encoder wheels on the rear of the winch motors were very slightly rubbing on the interior walls of the housing. Since these magnetic wheels were directly attached to the spindle of the motor and not the output shaft through the gearbox, they had a very low torque output, meaning that a very small amount of friction provided enough resistance to arrest the motors entirely. To rectify this issue, a special modification was made to this housing compared to all the other housings. On the three vertices of the rounded triangular profile, the central 2.5 cm of the side walls were expanded to the outer profile normally only used for the mounting holes. This provided an inner notch / cutout which allowed enough room on the interior for the encoder wheels to spin freely, while maintaining the overall profile of the robot. On the top and bottom of each of these notches, the housing returned to its original shape for 6.5 mm to provide enough room for a bolt / nut to fit when assembling segments together. This iteration upon the initial design rectified the issue, and was implemented as the final housing design.

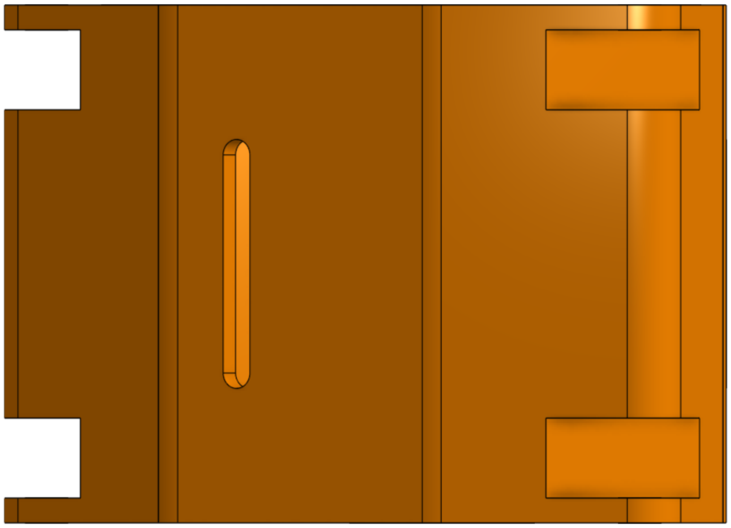


Figure 15: Final winch housing iteration: Side view showing the expanded notches on the side walls to allow extra space for encoder wheels

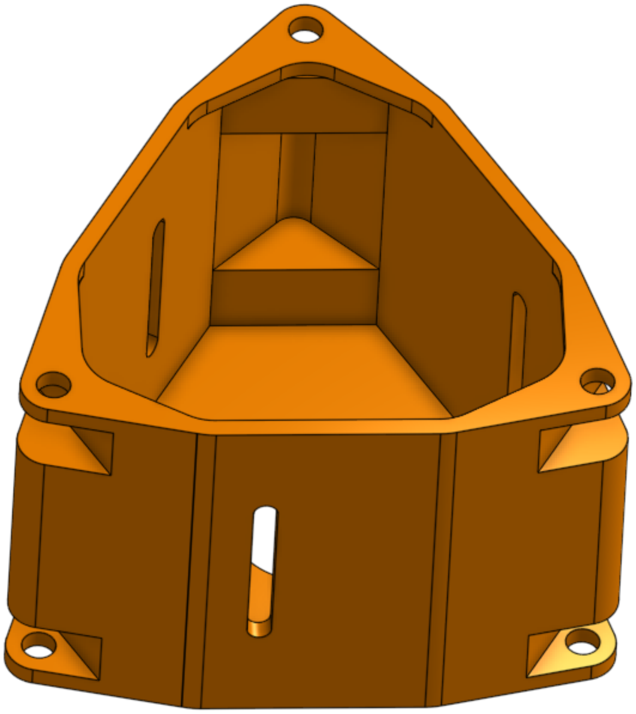


Figure 16: Final winch housing iteration: Angled top view showing interior of expanded notches

4.1.5 Adapter Plates and Additional Housings

To connect these new body segments to segments from the 2022 iteration which did not change, we designed two varieties of adapter plates. Specifically, one for mounting of the origami module, and one for mounting of the lead screw motor and gearbox. On either side of the origami modules, we designed a flat 2 mm thick plate with mounting holes for both the origami and other segments of the robot. This design was relatively simple.

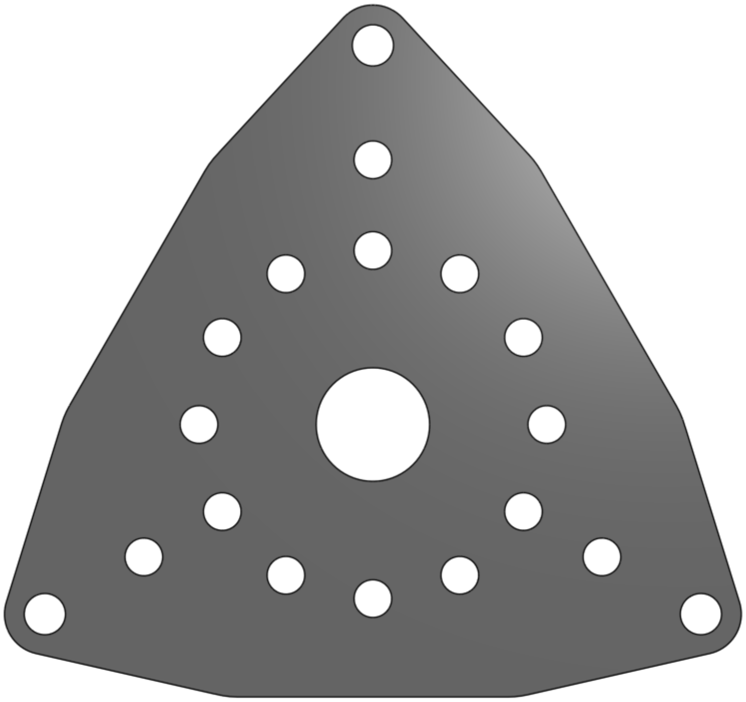


Figure 17: The flat origami mount plate top view

Additionally, for the mounting of the front lead screw motor, an alternate version of this mount plate was designed with a rectangular slot designed to fit snugly around the gearbox of the lead screw motor, restricting the rotational force to the lead screw itself.

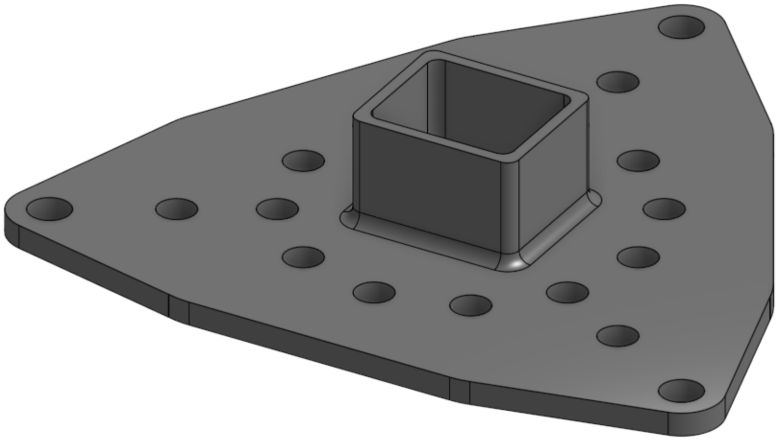


Figure 18: The adapter plate with rectangular gearbox slot

Initially, the version with gearbox slot was intended to be attached to the front end of the origami module, as the front lead screw motor was intended to be contained within the origami modules However, following the reordering of modules detailed in Section 4.1.7, a second of the flat adapter plate was fitted to the front of the origami module, and the second version was mounted to the top of an additional housing segment designed to protect the front lead screw motor. This segment was designed the same way as all other housings, following the profile and featuring one open side and one side with a 1.5 cm wiring hole.

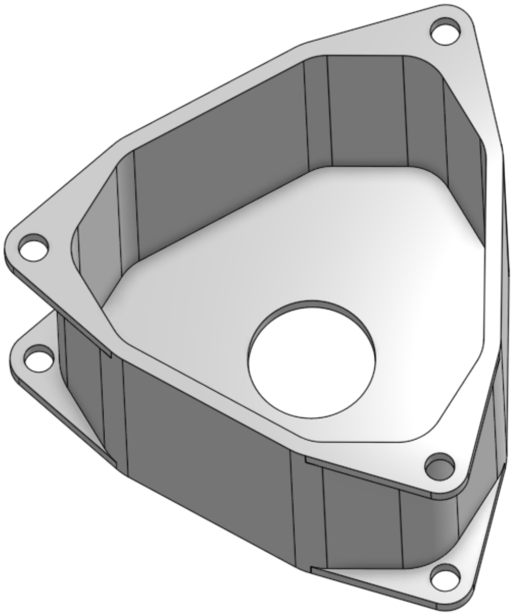


Figure 19: Front lead screw motor housing

The rear lead screw motor, however, was fitted on the outside of the rear wheel segment (Section 4.1.7). To protect this motor, a specialized housing was designed to fit onto the wheel segment lead screw retention shrouds (see Section 4.2). This housing is a cylindrical housing featuring a flat attachment plate at the bottom with a 2.35 cm outer diameter cylindrical shell with a 2 mm wall thickness that extends upwards 2 cm. It then tapers out to an outer diameter of 4.2 cm over the next 1.2 cm vertically, then continues vertically for 2 cm. This design is intended to fit an N20 motor, gearbox, and smart motor driver board. It also features a 1.5 cm wide by 0.5 cm tall rectangular cutout for the JST connector.

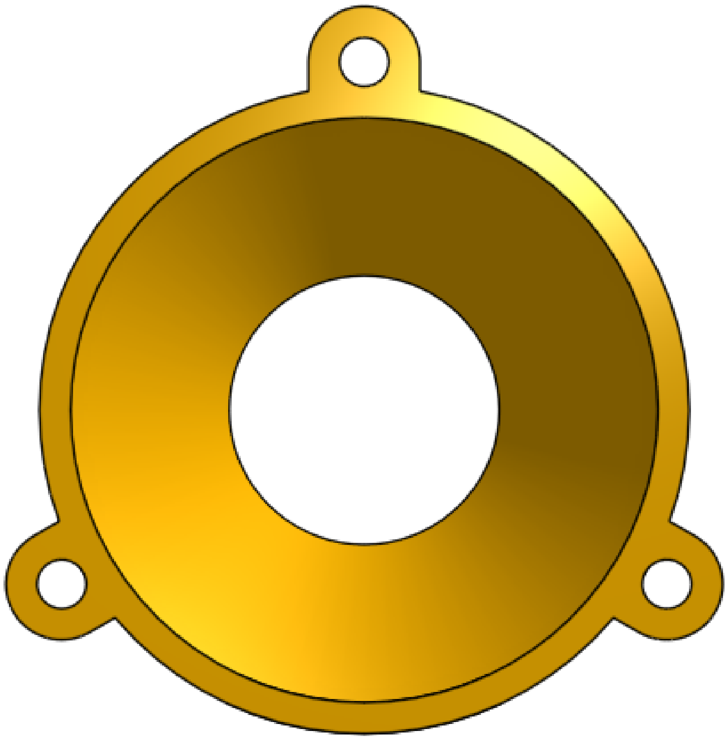


Figure 20: Rear lead-screw motor shroud: Top view

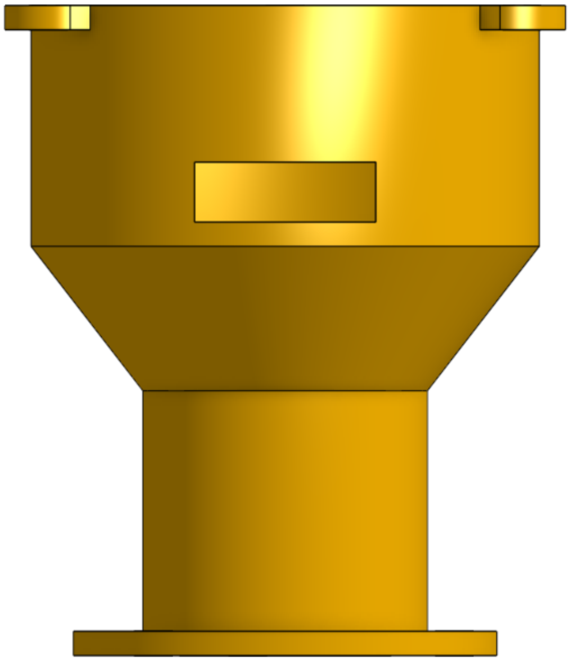


Figure 21: Rear lead-screw motor shroud: Front view

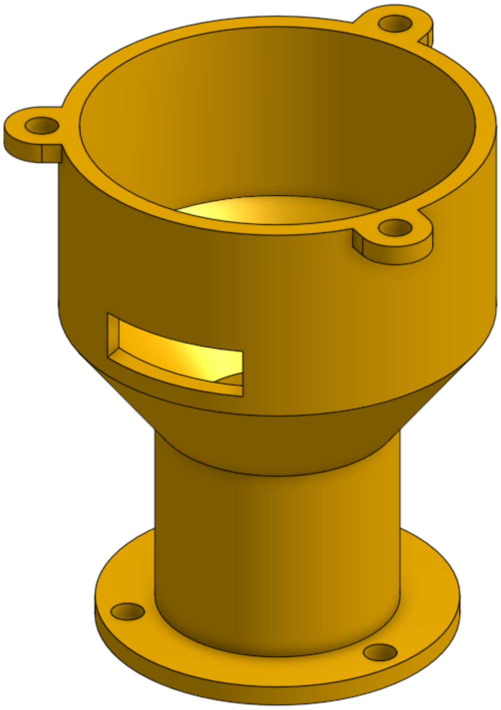


Figure 22: Rear lead-screw motor shroud: Isometric

4.1.6 Camera Housing

To facilitate the mounting of the camera module implemented in this iteration (see Section 4.4), a housing was designed to fit the board and chosen camera lens module. This housing was designed to attach to the motor segment lead screw retention shroud detailed in Section 4.2 such that it can be mounted at the very front of the robot.

The interior of the camera housing is 4 cm wide, 3 cm long, and 2.5 cm deep. Its walls are 2 mm thick around, barring a 1.5 cm wide 0.5 cm tall cutout for power cables. On the bottom of the housing is a round extrusion with notches for mounting to the 3 bolt holes to match the top of the wheel segment lead screw retention shroud. Finally, there are 2 flanges with bolt holes for mounting to the cap, which is simply a rectangle matching the top profile of the housing. On the underside is a rectangular extrusion to align the cap to the inner walls of the housing. One middle hole with a diameter of 9.8 mm is in the cap as well to snugly fit the camera lens.

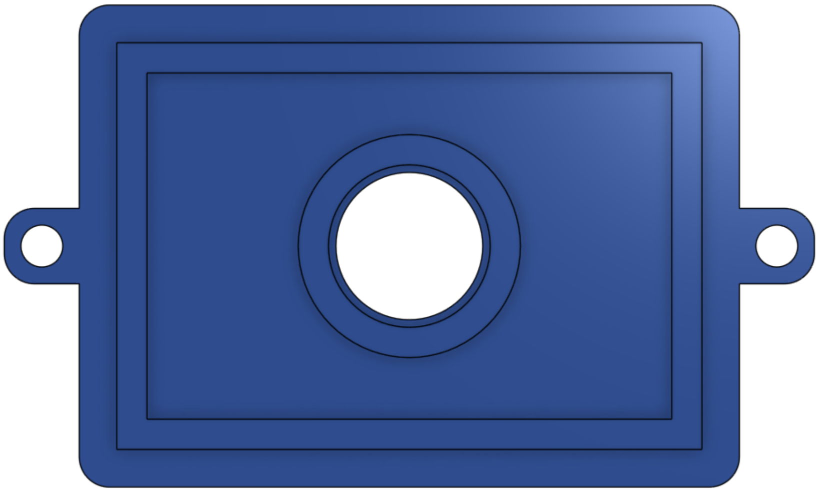


Figure 23: Underside of the camera housing cap

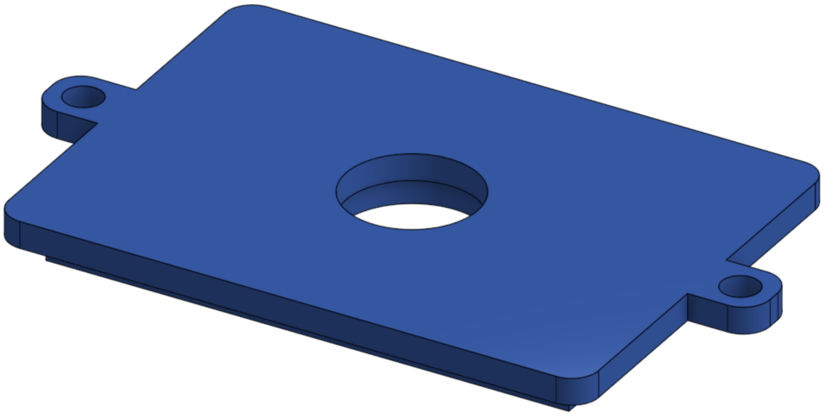


Figure 24: Isometric view of the camera housing cap

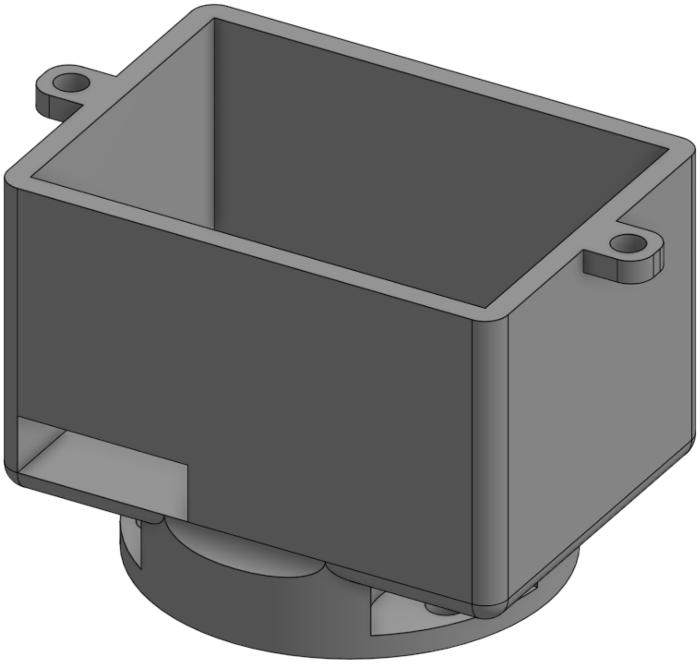


Figure 25: Isometric view of the camera housing

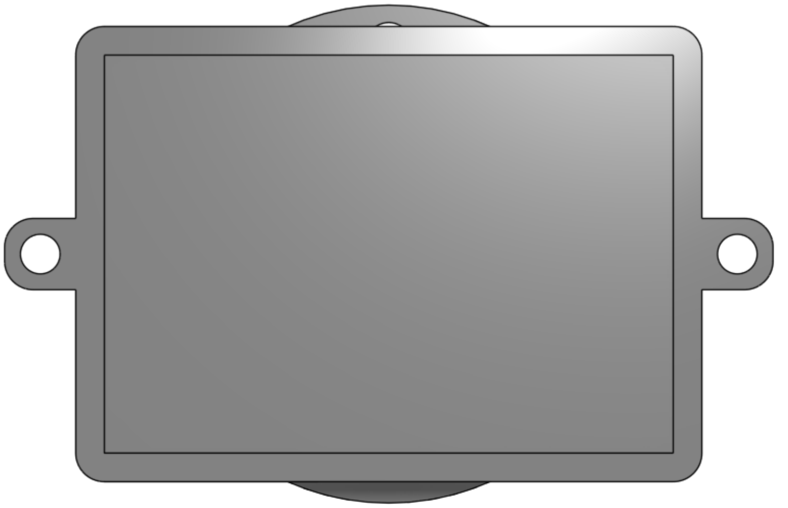


Figure 26: Top view of the camera housing

4.1.7 Segment Reordering

After redesigning the body segments and housings, the overall length of the robot increased significantly. Initially, the planned order of modules from rear to front would have been as follows:

1. Rear wheel module
2. Rear lead screw motor module
3. Battery module
4. Main board module
5. Winch module
6. Origami module (with front lead screw motor)
7. Front wheel module
8. Camera module

However, this ordering placed the origami segment incredibly far toward one end of the robot. In this orientation, bending of the origami module would not allow for the overall turning of the robot, as 5 modules were on one side of the origami with only 2 on the other. This meant that one of the rigid segments of the robot was too long to be pulled through a turn. To combat this, the robot was reordered in the following order from rear to front:

1. Rear lead screw motor module
2. Rear wheel module
3. Battery module
4. Main board module
5. Origami Module
6. Winch module
7. Front lead screw motor module
8. Front wheel module
9. Camera module

While this orientation did increase the overall length of the robot by moving one of the lead screw motors from inside the origami module to outside it, it did allow for better and effective turning of the robot as there were now a maximum of 2 modules between the origami module and each wheel segment. Additionally, removing the lead screw motor from inside the origami means that there is less chance of the origami bending damaging the motor or its driver board. This reordering of modules did require the inclusion of more power and signal wires running through the center of the origami module, however it provides significantly less impediment to bending than the motor which was previously inside the origami.

4.2 Wheel Segments

The expandable and contractible wheel segments introduced in the 2022 iteration of the CLARA robot were a marked improvement on the salamander bot it was based on. They allowed the robot to fit within pipes of diameters varying from 3.6” to 5.1”. However, the designs were not without their problems, and were able to be dramatically improved upon in this iteration.

4.2.1 Actively Limited Passive Suspension

In the 2022 iteration of the CLARA robot, there were two different models of wheel segments. One side was actively driven and actively extended and contracted. A central hub was threaded around a driven lead screw which moved the hub along the central axis of the robot. Specially designed motor housings were attached to the baseplate at the bottom corner, and an extension arm at the top, which in turn was attached to this central plate. This assembly created a slider-crank linkage which allowed the wheels to pivot toward or away from the central axis when the lead screw was driven. To allow for a small amount of damping, the extension arms were printed in TPU, a flexible filament.

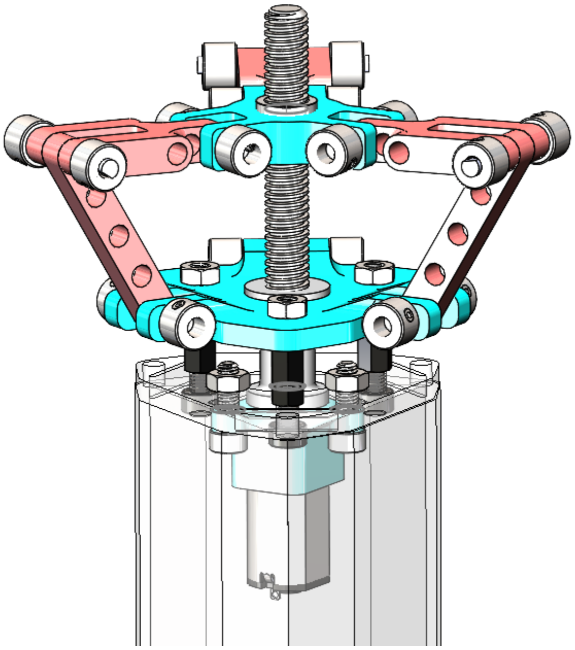


Figure 27: Slider-Crank mechanism CAD assembly rendering from 2022 Iteration Report [1]

On the other end of the robot was a non-driven, passively compressible segment. The linkage was quite similar to the active end. However, it had no motors, the central hub slid along the lead screw passively, and a compression spring sat around the lead screw shaft between the central hub and the base plate.

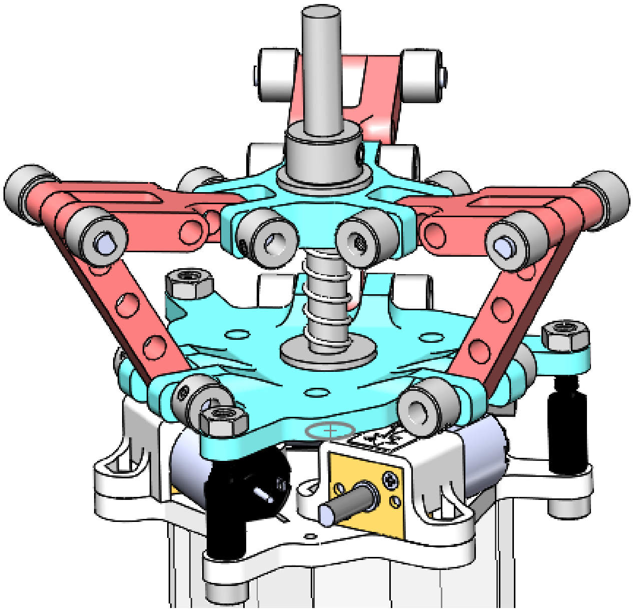


Figure 28: Passive end design CAD assembly rendering from 2022 Iteration Report [1]

These two modules, while functional, presented a variety of issues which we decided needed to be addressed to make this robot a functioning platform for further development and research.

First, having driven wheels on only a single side presents problems in the case of junctions or other openings in the pipe. When the driven end encounters a widening pipe, junction, or otherwise, it will no longer have grip on the inner walls of the pipe. In this scenario with the previous iteration's design, the robot would no longer be able to move, and would need to be recovered. This meant that this robot was not able to navigate a junction without intervention.

The second issue was that with only one side able to be actively compressed, the robot could only travel in one direction through junctions or pipe constrictions. If the robot were in a situation where it had to travel backwards and encountered a junction or sudden pipe constriction, it would not be able to actively contract the wheels to fit in the narrower pipe. In the case of a junction, when the pipe widened, the wheel linkage would decompress and increase in diameter. Then, when reaching the next pipe opening, it would again be unable to actively retract the wheels to fit.

These flaws considered, we decided to modify the active motor segment to function as an actively-limited passive suspension with driven wheels, as well as duplicate it to the other side. This would eliminate the loss of control introduced when one side loses grip, as the other side would be able to maintain grip and push or pull the robot until the lost side could regain contact. Additionally, making both ends able to expand or contract independently would mean that one side could contract without the robot losing grip and sliding down the pipe.

4.2.2 Lead Screw Retention Shroud

The first major modification made to the active motor segment was the implementation of a lead screw retention shroud. In previous iterations, the lead screw in the active wheel segment was supported at only one end by the motor adapter. However, this lack of support on the other end meant that unequal pressure on the wheels of the robot could shift the lead screw, putting pressure on the motor mount points, and causing the linkage to bind. To rectify this, a shroud was designed to support the far end of the lead screw while not impeding the linkage members.

Additionally, this retention shroud features bolt holes on the top surface, as well as a flat face. The purpose of this is to allow for the mounting of segments or modules on either end of the motor segment. In the previous iteration, the wheeled segments were required to be located at the ends of the robot. However, with this change, we were able to mount a lead screw motor and a camera module on the outside of the motor segments.

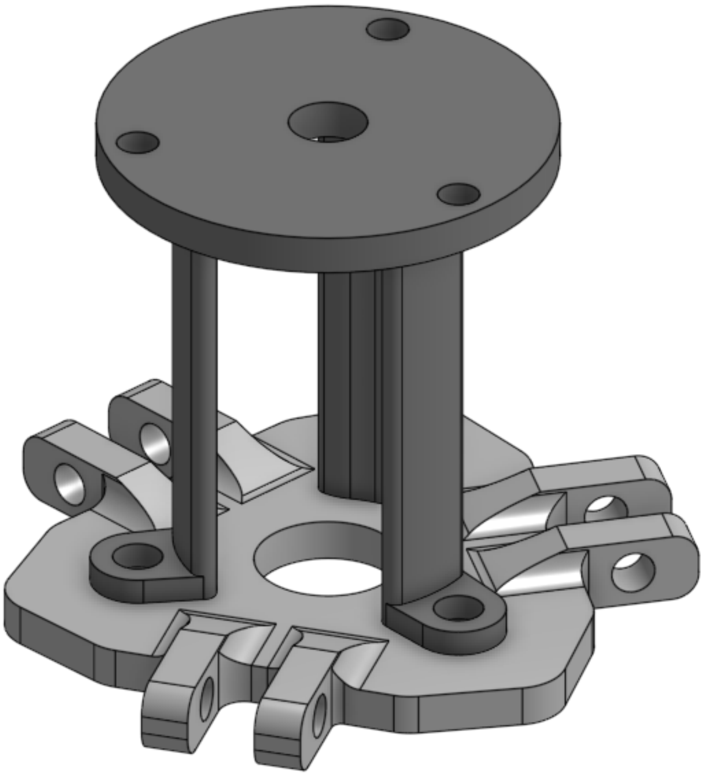


Figure 29: Lead screw retention shroud CAD model attached to wheel segment base plate

4.2.3 Limiting Screw Rider

As mentioned previously, the wheel segments were also modified to combine both the passive suspension aspect of the passive section, and the expansion and contraction aspect of the active section. To achieve this, the central hub attached to the linkage itself was made to passively slide along the lead screw, while another limiting plate was placed on the outside of this central hub and threaded onto the lead screw. Additionally, a compression spring was added around the lead screw between the passive slider and the base plate. In this way, the wheels of the segment could always be passively compressed. However, by driving the lead screw, they could be actively compressed or extended to increase their maximum extension point. The benefits of this are preventing impediment of motion from unexpected constrictions or expansions in a pipe, as well as consistent pressure on the interior surface of the pipe.

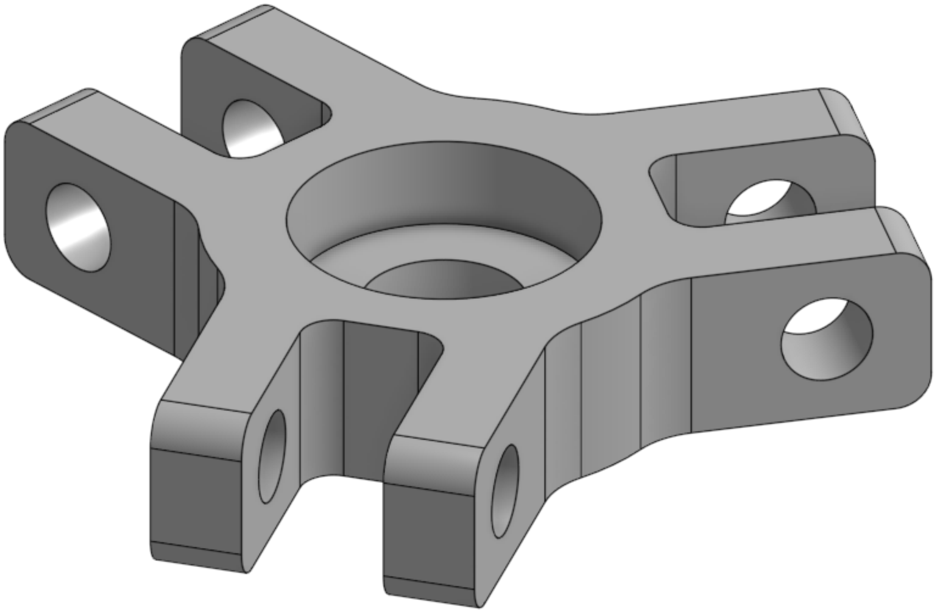


Figure 30: Passive slider hub CAD model: Top Isometric

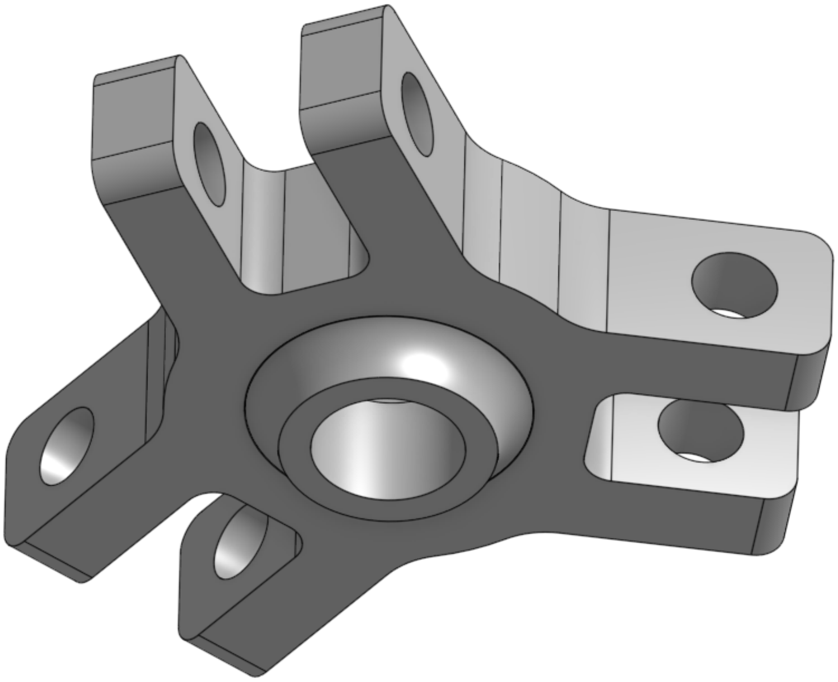


Figure 31: Passive slider hub CAD model: Bottom Isometric

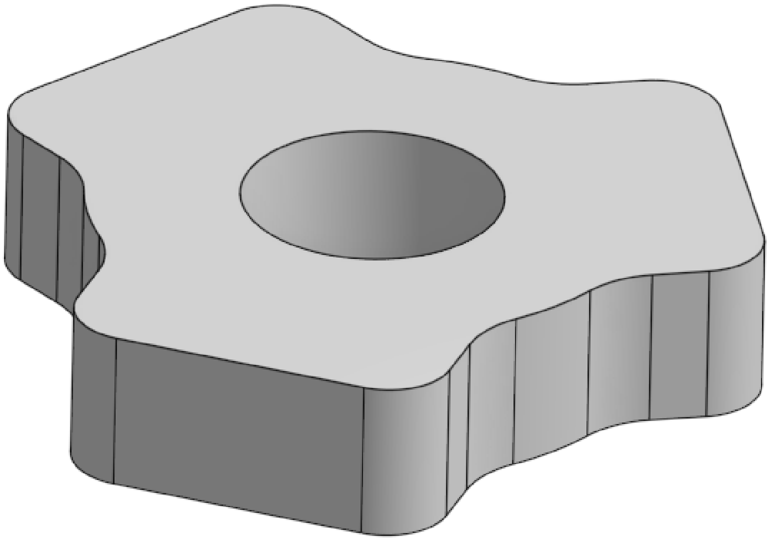


Figure 32: Threaded limit plate CAD Model: Isometric (seen without central threaded brass fitting)

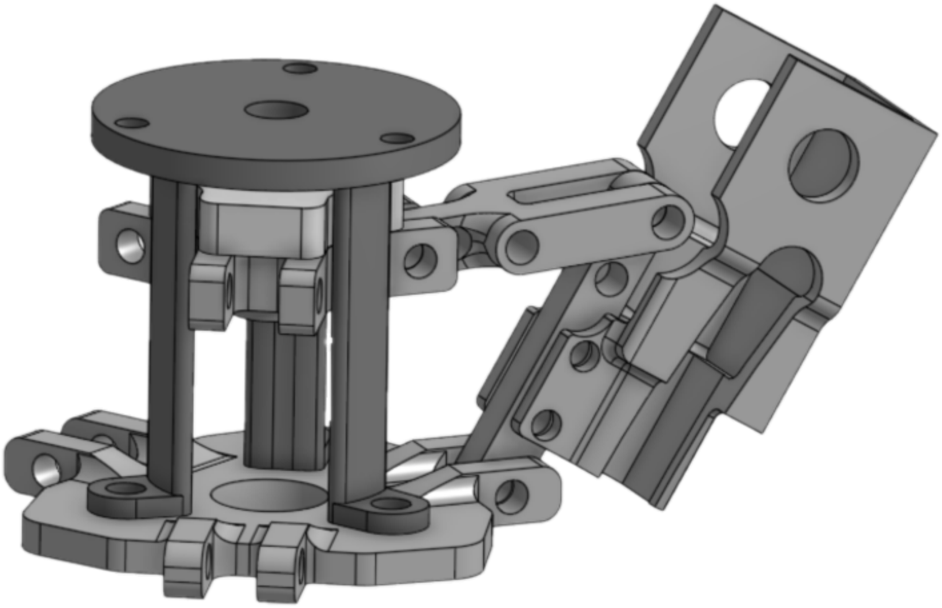


Figure 33: Actively limited passive suspension segment CAD model with single wheel arm (without lead screw or compression spring)

4.2.4 Lead Screw Adapters

In the 2022 iteration, the adapters made to transfer rotation force between the N20 lead screw motors and the lead screw itself were FDM printed in PLA, and presented issues with slipping. They had a D-shaft channel in which the motor output shaft was fit, and a hole on the opposite side that the lead screw was directly threaded into. Unfortunately, since the lead screw was threaded in directly, when the motors attempted to turn a certain way, they would over time unscrew the lead screw from the adapter, and eventually disconnect entirely. To rectify this, a new adapter was developed, intended instead to transfer torque from the lead screw motor to a shaft collar *on* the lead screw. Additionally, the part of the adapter designed to fit around the shaft collar was a press-fit, and featured a hole for access to the shaft collar's set screw. They were also printed in Tough 1500 resin [8] to increase quality and strength.

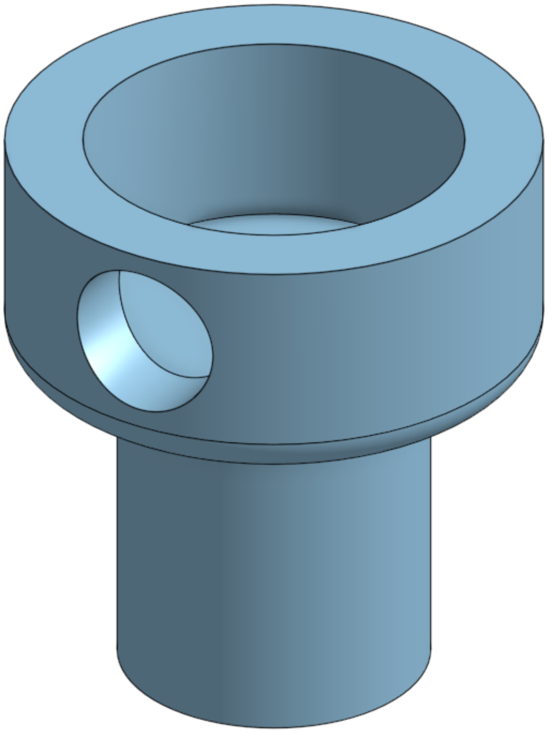


Figure 34: Lead screw to motor adapter CAD model: Top isometric

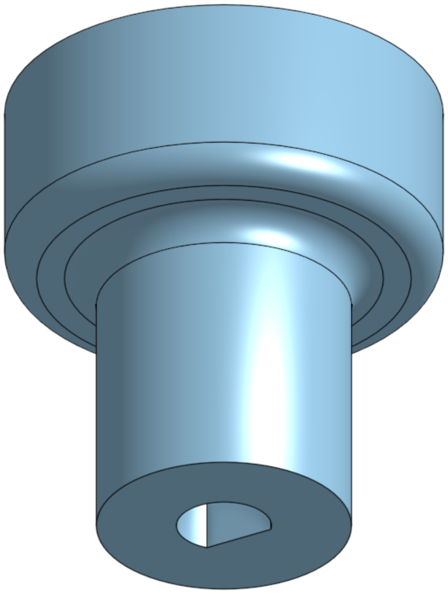


Figure 35: Lead screw to motor adapter CAD model: Bottom isometric

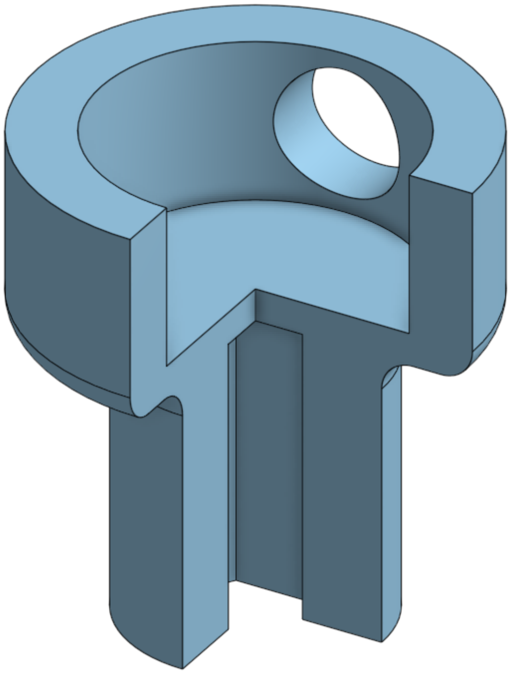


Figure 36: Lead screw to motor adapter Cad model: Isometric section view

4.3 Winch Module

The winch module proved to be one of the most challenging modules to modify to fit within the new body profile of the robot. Featuring 3 motors, each with a gearbox, winch drum, and wires, this module has the most components of all the modules we desired to fit within this profile. Additionally, we intended to design this new module to fix the issue presented by the previous iteration with cable friction on the origami module.

4.3.1 Winch Orientation

In the prior year's implementation of the robot, the winches which retracted the cables for the flexing of the Yoshimura origami segment presented several issues which warranted their redesign and reorientation. First, their horizontal orientation extended them beyond the newly designed body profile. Second, when the winch drums were attached to the motors, they extended far beyond their mount plates, providing pieces which stuck out to the sides and provided the potential to catch on obstacles and either damage the robot or hinder its movement. Third, the dramatic angle at which the winch cables turned upon exiting the channels in the origami module meant that applied force to the cables by the winches was consistently translated into friction of the cables against the plastic of the origami. Over time, this friction led the cables to create a 'sawing' effect on the origami modules and cut through the plastic, allowing the cables to break free of their channels and rendering the origami modules ineffective. To rectify these issues, we designed a new winch housing which would fit within the body profile, reorient the winches, and better align the cables within the origami channels. Additionally, new winch drums were designed and printed out of Tough 1500 resin [8] to provide added strength and quality.

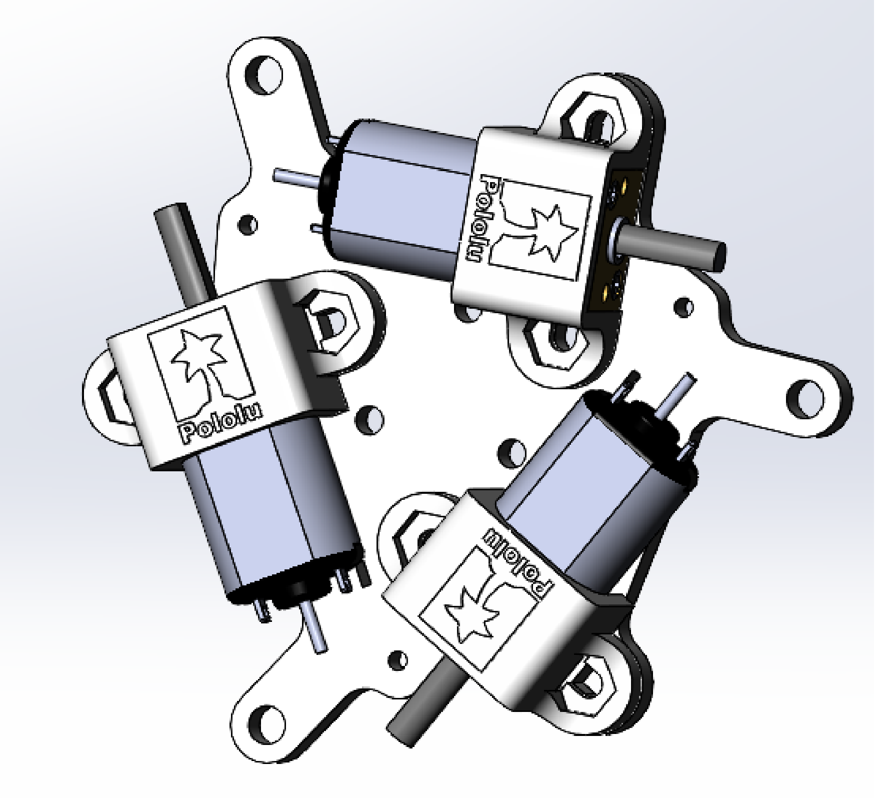


Figure 37: The 2022 iteration of CLARA's winch motor orientation and mount plate [1]

Upon inspection and analysis of the 2022 iteration of the winch module, the triangular pattern of the motors was taken into consideration and deemed to be quite a space-efficient orientation. However, the width of the N20 motors used meant that this orientation would not fit within the newly implemented body profile. To rectify this, the motors were rotated 90 degrees radially along their own axis, meaning they would each be mounted to a side wall of the new housing. This allowed the motors to be moved inward slightly, reducing the distance from the central axis of the robot to the outermost point, and allowing them to fit within the profile. This new orientation, combined with the new winch drums detailed in section 4.3.2, also rectified the issue of cables cutting through the origami, as the winch drums now lined up more linearly with the cable holes in the origami module, meaning there was less friction between the cable and the origami.

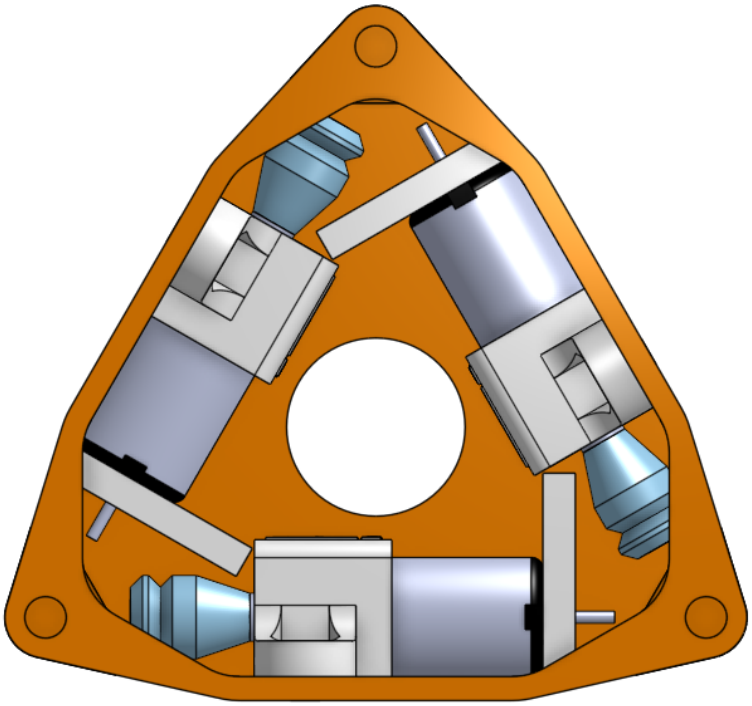


Figure 38: Top down view of the new winch motor orientation with winch drums attached

4.3.2 Winch Drums

To help the winch module fit within the new profile, new winch drums were designed to be about half the size of the previous brass drums. These drums were SLA (stereolithography) printed using Formlabs Tough 1500 Resin [8] rather than FDM printed out of PLA to provide additional strength and quality. This added strength was deemed necessary due to the smaller size of the winch drums to allow them to withstand the forces placed on the cable by the motors and the spring resistance of the origami module. These winch drums feature a central press-fit hole for a 1.5 mm D-shaft and a maximum diameter of 7 mm. They are 1 cm tall, the same length as the driven shaft of the N20 motors, and taper to a diameter of 5 mm at the top and 6mm at the base. 7.5 mm from the base, the drums also taper to a diameter of 5 mm over 1 mm lengthwise, then taper back out over another 1 mm. This created a 2 mm wide, 2.5 mm deep V-channel intended for the wrapping of the winch cable.

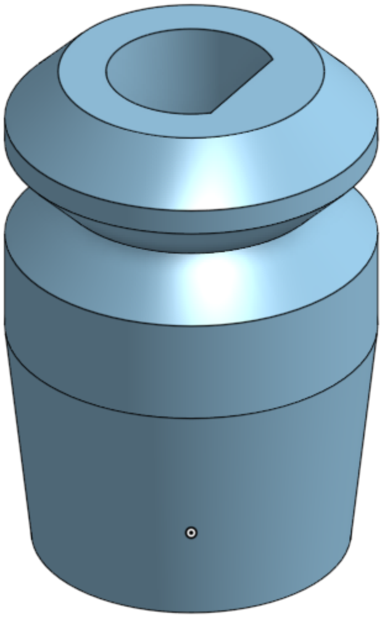


Figure 39: New winch drum design

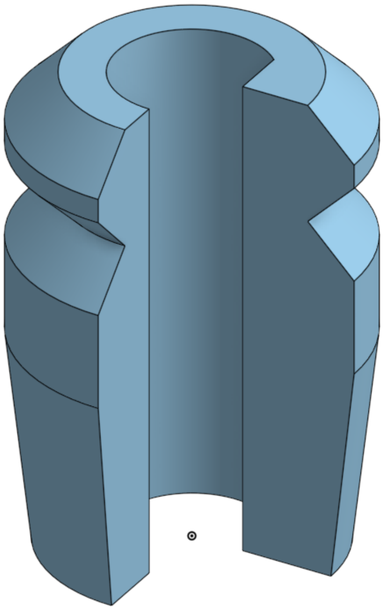


Figure 40: Section view of new winch drum design

4.4 Camera Choice

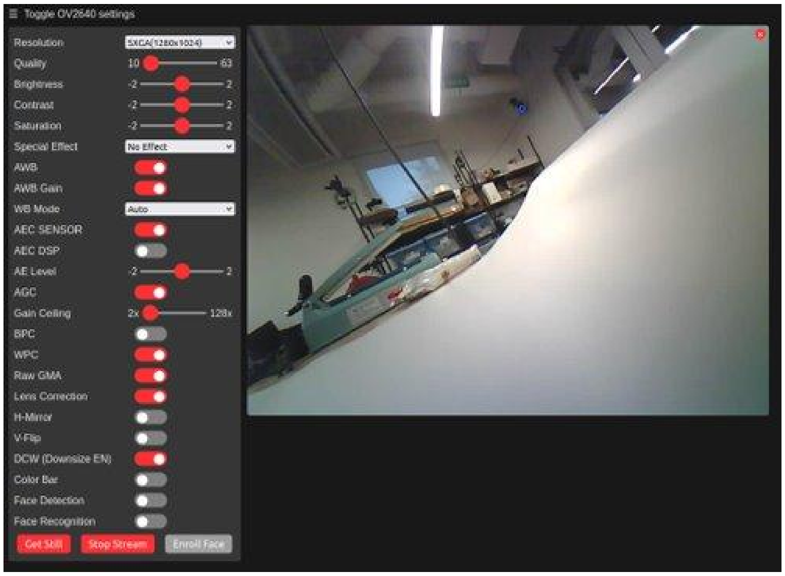
To provide functionality as a pipe inspection robot, a basic sensor was deemed essential for this implementation to allow for the robot to provide data to the operator about its position in the pipe, as well as the pipe itself. To accomplish this, we needed a camera that was small, simple, and robust.

4.4.1 ESP-32 Cam

We selected the ESP32-CAM module for this application due to its small size and wireless communication capabilities. We purchased an ESP32-CAM module with the programming shield to allow us to upload custom code to the module. Additionally, we purchased a third party fisheye lens to increase the field of view of the camera and allow us to view and further inspect the inside surface of the pipe.

4.4.2 Code / Communication Method

The code used in our application was a slightly modified version of the Espressif ESP32-Cam web server example code [3]. This code takes the video captured by the camera and uploads it to a web server hosted on a WiFi network specified in the code. However, to simplify things, and allow the robot to be used without a direct connection to an external WiFi network, the code was modified. Instead of connecting to an external network, the ESP32-Cam was set to act as its own WiFi station. In this way, the operator laptop can be connected to the new CLARA Cam Access Point network, and the live feed can be accessed by entering the local IP address of the ESP32-Cam network “CLARA Cam Access Point”, or 192.168.4.1, into a browser window.



Resolution: SXGA(1280x1024)
Quality: 10 – 63
Brightness: -2 – 2
Contrast: -2 – 2
Saturation: -2 – 2
Special Effect: No Effect
AWB ☑
AWB Gain ☑
WB Mode: Auto
AEC SENSOR ☑
AEC DSP ☐
AE Level: -2 – 2
AGC ☑
Gain Ceiling: 2x – 128x
BPC ☐
WPC ☑
Raw GMA ☑
Lens Correction ☑
H-Mirror ☐
V-Flip ☐
DCW (Downsize EN) ☑
Color Bar ☐
Face Detection ☐
Face Recognition ☐

Figure 41: Live video feed example from ESP32-Cam module onboard CLARA robot [3]

4.5 Electrical Modifications

To support the number of mechanical modifications made, a few electrical changes were made, including new batteries, the implementation of a main breaker, and a general rewiring to support all new components.

4.5.1 Battery Change

To allow the battery pack to fit within the new body profile, the single 1000 mAh 7.4V LiPo battery was replaced by a pack of three 250 mAh 7.4V LiPo batteries. While this does represent a slight decrease in overall battery capacity, the batteries were wired in parallel to maintain the 7.4V output while increasing maximum current output.

4.5.2 Main Breaker

The implementation of a main breaker was one of the most important additions to the robot we made in this iteration. In the previous iteration, the only method of turning the robot on or off was to unplug or plug in the battery. In the new version, the batteries are not able to be easily unplugged due to the design of the battery housing. However, this is not an issue due to the implementation of the main breaker.

4.5.3 Rewiring

An overhaul of the wiring of the robot was done to fortify connections and ensure insulation between wires. Many JST connectors were used between components to allow for disconnection between modules if necessary. Additionally, a new 5V regulator was wired in parallel with the main board to provide power to the camera.

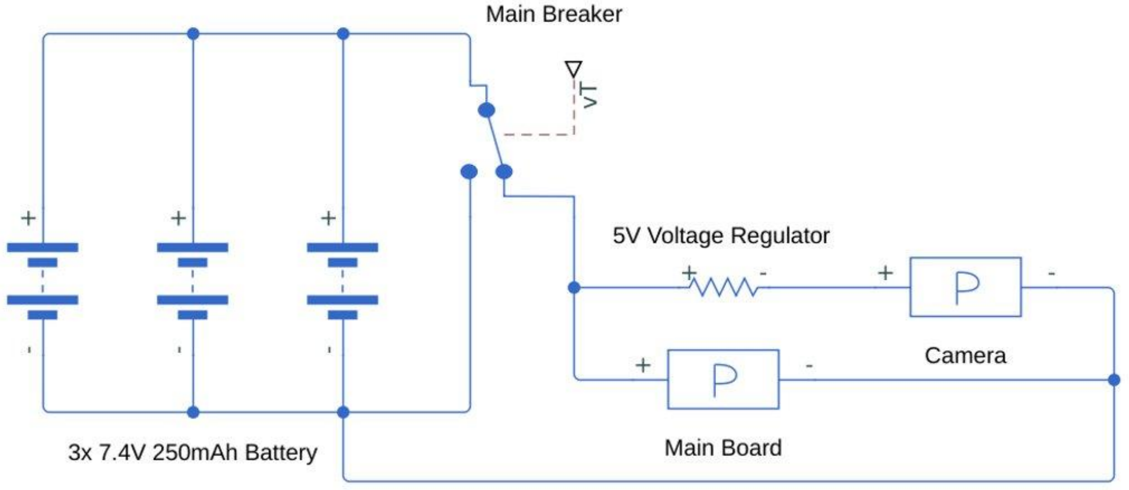


Figure 42: A basic wiring diagram of the 2023 iteration of the CLARA robot. The main board and camera are represented as constant power loads

4.5.4 Smart Motor Driver Board Programming

Due to the implementation of the new driven wheel segment on the rear of the robot, four new N20 motors were added to the robot to provide proper function. To facilitate this, four new smart motor driver boards were attached to motors and programmed with specific IDs for use in I2C communication. The process of programming these smart motor driver boards required an Arduino Uno with a 6 pin TagConnect (TC2030-NL) ISP connector.

Prior to programming, the TadConnect wire was connected to the ports on the Arduino Uno according to the mapping of the Nano ports to the onboard ATMega328-AU pinout.

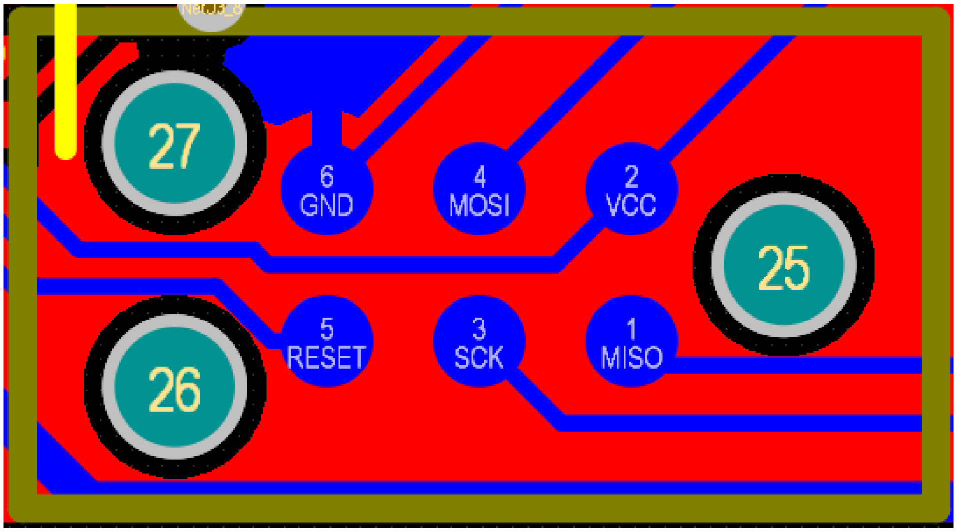
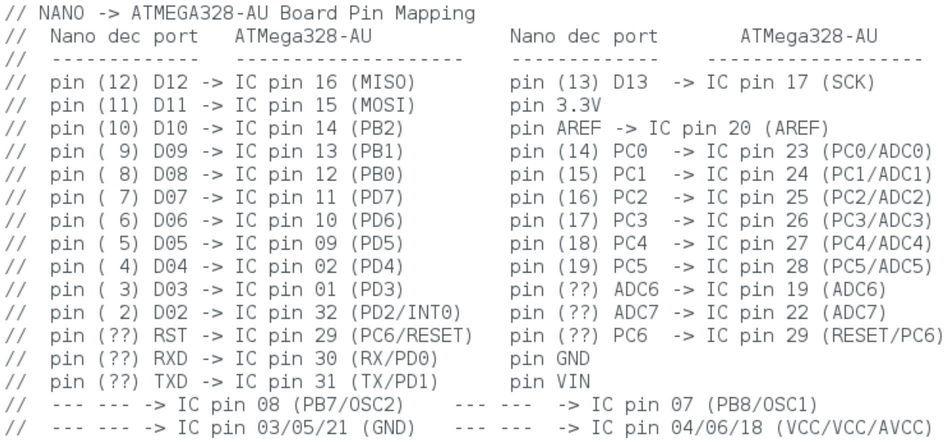


Figure 43: Six Pin ISP Contact Pads on the smart motor driver boards [1]



```
// NANO -> ATMEGA328-AU Board Pin Mapping
//  Nano dec port   ATMega328-AU           Nano dec port       ATMega328-AU
//  -------------   --------------------   -------------    -------------------
//  pin (12) D12 -> IC pin 16 (MISO)       pin (13) D13  -> IC pin 17 (SCK)
//  pin (11) D11 -> IC pin 15 (MOSI)       pin 3.3V
//  pin (10) D10 -> IC pin 14 (PB2)        pin AREF -> IC pin 20 (AREF)
//  pin ( 9) D09 -> IC pin 13 (PB1)        pin (14) PC0  -> IC pin 23 (PC0/ADC0)
//  pin ( 8) D08 -> IC pin 12 (PB0)        pin (15) PC1  -> IC pin 24 (PC1/ADC1)
//  pin ( 7) D07 -> IC pin 11 (PD7)        pin (16) PC2  -> IC pin 25 (PC2/ADC2)
//  pin ( 6) D06 -> IC pin 10 (PD6)        pin (17) PC3  -> IC pin 26 (PC3/ADC3)
//  pin ( 5) D05 -> IC pin 09 (PD5)        pin (18) PC4  -> IC pin 27 (PC4/ADC4)
//  pin ( 4) D04 -> IC pin 02 (PD4)        pin (19) PC5  -> IC pin 28 (PC5/ADC5)
//  pin ( 3) D03 -> IC pin 01 (PD3)        pin (??) ADC6 -> IC pin 19 (ADC6)
//  pin ( 2) D02 -> IC pin 32 (PD2/INT0)    pin (??) ADC7 -> IC pin 22 (ADC7)
//  pin (??) RST -> IC pin 29 (PC6/RESET)  pin (??) PC6  -> IC pin 29 (RESET/PC6)
//  pin (??) RXD -> IC pin 30 (RX/PD0)     pin GND
//  pin (??) TXD -> IC pin 31 (TX/PD1)     pin VIN
//  --- --- -> IC pin 08 (PB7/OSC2)    --- ---  -> IC pin 07 (PB8/OSC1)
//  --- --- -> IC pin 03/05/21 (GND)   --- ---  -> IC pin 04/06/18 (VCC/VCC/AVCC)
```

Figure 44: Pin mapping from Arduino Uno ports to ATMega328-AU board [1]

For example, the wire on the TagConnect cable which would connect to contact pad 4 was connected to the D11 pin on the Arduino Uno board, as both correspond to the MOSI pin on the respective ATMega328-AU ICs. Once all these connections have been established, programming can begin.

The code uploaded to the smart motor driver boards is the *SAMI_nonreversed.ino* file located in the CLARA robot repository. This code should be opened in the Arduino IDE, with the following settings. Under the ‘Tools’ tab, the selected ‘Board’ should be the “Arduino Uno”. The ‘Programmer’ selection should be “Arduino as ISP”. The ‘Port’ selected should be the USB port to which the Arduino Uno is connected to the laptop.

To program a smart motor driver board, the six-pin TagConnect wire should be connected to the contact pads on the smart motor driver board, and the ‘address’ variable on line 67 of the *SAMI_nonreversed.ino* file should be changed to the desired hexadecimal address that you wish to program into the smart motor driver board to be used in the I2C protocol. When all connections are made, the upload button can be pressed and the board should be programmed. Afterwards, the board can be connected via I2C to the TinyPICO main board, and an I2C device scanner can be run. If the serial output displays that an I2C device was found at the desired address, programming was successful.

4.6 Software and Control Changes

Similar to the electrical changes made, a few software changes were made to support the addition of new motors and changes in components. Some new controls were added to modules which did not require them previously, some controls which were deemed unnecessary were removed, and some new motors were added to pre existing controls.

First, the three new drive motors were added to the drive forward and drive reverse controls, as it was desired for all six drive wheels to move in unison. We do not believe there is any scenario in which it would be preferable to only have half the motors driving, so that functionality was not implemented.

Secondly, a new control was added for the new rear wheel segment lead screw. Whereas the front wheel segment is expanded by holding the ‘A’ button and contracted by holding the ‘Y’ button, the rear wheel segment is expanded by holding the ‘B’ button *and* the ‘A’ button, and contracted by holding the ‘B’ button *and* the ‘Y’ button. More simply, by holding the B button before controlling the front wheel segment, you switch to controlling the rear wheel segment.

Finally, some controls were deemed unnecessary and even confusing, so they were removed. Previously, pressing one of the diagonal directions on the d-pad on the controller would expand or contract multiple winch cables at once. However, during testing, these controls were activated very often by accident, and almost never intentionally. Since contracting a winch accidentally could result in over-contracting a winch cable and potentially damaging the system, it was decided it would be better to remove the controls entirely.

Gamepad Button	Serial Command Code	Resultant Control
Right Bumper	8	Drive Forwards
Left Bumper	9	Drive Backwards
D-Pad LEFT	24	Contract Cable 1
D-Pad DOWN	25	Contract Cable 2
D-Pad RIGHT	26	Contract Cable 3
B button + D-Pad LEFT	18	Extend Cable 1
B button + D-Pad DOWN	19	Extend Cable 2
B button + D-Pad RIGHT	20	Extend Cable 3
A button	4	Expand Front Wheels
Y button	1	Contract Front Wheels
B button + A button	28	Expand Rear Wheels
B button + Y button	27	Contract Rear Wheels

Table 2: Final robot controls with serial command codes

5. Results

5.1 Mechanical Overview

This section delves into the results of both our implemented changes in addition to the data and analyses gained from testing. We share our successes while acknowledging that there were some shortfalls or unintended consequences as a result of our changes.

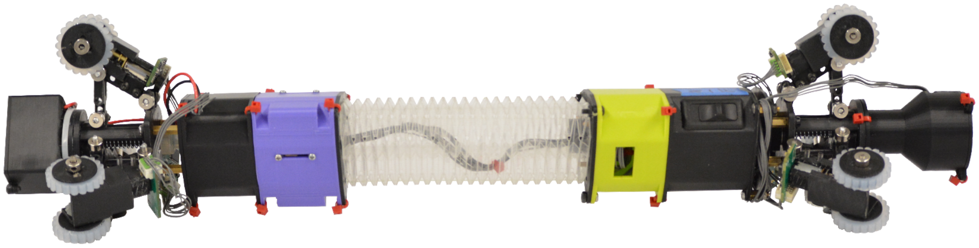


Figure 45: Side profile of the final completed 2023 CLARA robot iteration

5.1.1 Casing / Profile

The redesigns of the robot casing as well as the development of the new, slimmer body profile proved to be an effective method of combating the issues we observed in the previous iteration. The new casing provides adequate physical protection to vital robot components, as well as keeping them closer to the core axis of the robot. This reduced profile also works to improve the bending angle of the robot and improve the overall ‘finished’ appearance of the robot.

In addition, we believe that the new casing and consistent shape of the robot provides an easier platform for the robot to be waterproofed in the future. As detailed in section 7.1, we believe waterproofing would be a valuable avenue of future development. It is our belief that the consistent body profile would help facilitate this process.

5.1.2 Wheel Segments

The wheel segments underwent several changes which we believe to be incredibly beneficial to the overall function of the robot. The duplication of the actively driven module to both sides of the robot not only increased power output and grip, but also allowed for easier maneuvering of junctions and gaps in pipes. Additionally, modification of these segments to be actively retractable as well as passively compressible further improves maneuverability, while maintaining the benefits seen in the previous iterations wheel segments.

However, while these segments were improved upon, we were not able to successfully redesign the segments with protection of the smart motor driver boards in mind. Due to the nature of these segments, they would not and should not be able to fit within the newly developed profile of the robot. Development of a protective casing for these modules that does not impede their functionality or the movement of the linkage would require further research and testing which we were unable to accomplish.

5.1.3 Winch / Origami

After redesigning the winch system that controls the origami continuum module, we were able to place all of the winches within the consistent profile of the origami, therefore lining up the strings concentrically with the channel created in the origami. This has eliminated the issue of the winch string cutting the body edges due to the angle created.

The origami body of the initial iteration of the system had sustained damage due to friction and rubbing caused by the winch string to control the origami bending. The only body was the attached body, so we laser cut new sheets of Dura-Lar, learned how to fold the module, created a new one to attach in addition to one extra for quick replacement in case of extensive damage, in addition to extra unfolded sheets for the next team to learn to fold. For a number of the new parts we designed and created, we produced extra pieces to enable the team to quickly replace and test, rather than figuring out the production process and waiting for usable parts.

5.1.4 Battery Segment

The finalized battery module was composed of 3, 7.4V 250 mAh batteries, a 250 mAh decrease from the original lone 7.4 V 1000 mAh batteries. The batteries were wired in parallel to maintain the 7.4V output while simultaneously increasing the maximum current output.

Although the battery capacity decreased, it allowed us to use smaller batteries and arrange them such that they fit in one of the standard casing modules with small edits to allow an egress for the wires. Ultimately, future iterations will have to heavily consider the capacity of the system's power supply as the robot is untethered, and will require a quite hefty battery for long exploration missions. Regardless, this change to the battery segment was beneficial to creating a streamlined profile and removing a large protrusion that limited the navigation of the system

5.1.5 Camera Effectiveness

As mentioned previously, the implementation of a camera module was an essential contribution of this iteration of the CLARA robot. The addition of a camera added functionality previously not present on the CLARA robot, allowing for the intended inspection and exploration of pipe networks in situations where the robot itself is inaccessible to the operator. We were successfully able to implement this camera module with code providing a live video feed to the operator of the robot. However, we were unable to complete significant testing of the strength of this video connection. Therefore, the effectiveness of the camera in providing live video to the operator whilst the robot is underground is yet to be determined fully.

5.2 Performance

Following the completion of the 2023 iteration of the CLARA robot, multiple performance metrics were identified which would determine the robots success and effectiveness. These metrics measure both improvements over the previous iteration, as well as some new metrics.

5.2.1 Junction Maneuvering

The previous iteration of the robot was stated to have been able to maneuver through a pipe junction successfully. However, upon returning the previous iteration to functionality at the beginning of the project, we were unable to replicate this behavior due to mechanical failures and issues. The completed 2023 iteration, though, has successfully maneuvered through a pipe junction without external influence. This motion notably did require the improvements made to the wheel segments of the robot, as well as their duplication onto the previously passive end. The junction maneuvered was another pipe intersecting the main path of the robot at roughly a 45 degree angle.

5.2.2 Payload Towing Capacity

To act as a basis for one of our suggested future works, we measured the maximum payload weight towable by this iteration of the robot. This would act as proof of concept, showing that should a future team wish to implement possible payloads for testing and inspection of pipe networks, it would be possible. To test this, the robot was placed vertically in a pipe and masses were hung from the rear of the robot through the bottom of the pipe. The maximum measured mass towable by the robot before substantial wheel slip was seen was approximately 500 g.

5.2.3 Increased Bending Angle

In the previous iteration of the robot, the maximum bending angle of the origami module was approximately 86 degrees. However, following the improvements made to the casing and the narrowing of the overall body profile, this bending angle increased to approximately 150 degrees. This demonstrates a significant increase in bending angle, increasing potential for improved maneuverability. Unfortunately, we were limited to the testing of example ‘pipe networks’ we had available, and we did not have any 90 degree junctions or more to test the robots capability to traverse through.

5.3 Drawbacks

5.3.1 Length Increase

One major drawback of the 2023 iteration of the CLARA robot over the previous iteration is a fairly dramatic increase in overall body length. While the exact overall body length of the 2022 iteration is not known, it can be approximated to around 13” long. The 2023 iteration, however, is approximately 19” long, representing an increase of 6” or half a foot. This is a fairly dramatic increase in length, posing a potential threat to maneuverability. However, thanks to the reordering of body modules, this length increase has not shown much of an increase in difficulty of motion.

5.3.2 Weight Increase

Another drawback seen in the 2023 iteration is an overall mass increase. The previous iteration had a mass of around 500 grams, while the new iteration’s mass is approximately 670 grams, representing an increase of around 170 grams or 34%. This could present issues with grip and vertical motion, as increased mass requires more motor power to move. However, we saw that the robot was able to tow approximately 500 additional grams (see Section 5.2.2), meaning it could theoretically tow its previous iteration. Therefore, we do not believe this mass increase will be too detrimental to overall robot function.

6. Discussion

6.1 Results Overview

Though we did not meet every goal we set out to achieve, the outcome of our work and testing demonstrates a functional system with improved mechanical function, robustness, sensor feedback and insightful future work recommendations.

6.2 Testing

Though much of our work could not be tested in a quantifiable manner, much of our testing was performed by using the robot as intended, and identifying parts that broke or did not work as intended.

6.2.1 Mechanical Function and Robustness

Throughout the development of the robot, we conducted a number of tests, some inadvertently that allowed us to gain a deeper understanding of the impact of our work as well as acknowledging shortcomings and opportunities for future work. Through general testing of locomotion, suspension limitation and origami manipulation, we were able to identify areas where we needed to reconsider our approach. Initially, we connected our new winches to fishing line that had a lower weight rating than the previous as we were unable to find the previously used line. After numerous times of snapping, we were lucky to get access to stronger line to use for our cables, and no longer experienced that issue. The same went for some of the pieces we 3D printed that had manufacturing flaws we initially missed.

6.2.2 Camera Addition

The addition of a camera is a large step towards providing functionality and capabilities necessary to actually inspect real-life pipe systems. The camera provided live video feed with decent quality which can be a strong aid in navigation. However, the quality of the camera would not suffice if being used to identify pipe conditions. Although it may be able to visualize major cracks, damage or blockages, the quality is not sharp enough for thorough data collection and identification of less easily visible problems. We were unable to develop a quantifiable test as we wanted to test connection strength through walls and such, but any results would be less accurate as materials, wires and pipes within the wall could vary and skew our results.

6.4 Project Setbacks

Though there were many successes as a result of our work, there were also extensive setbacks during the timeline of our work that we feel had held us back from achieving all of our intended goals. As engineers, we want to acknowledge the hurdles we faced to share our experience and hopefully benefit future work.

At the start of the academic year, we were unable to connect with our advisor as effectively as we would have liked due to his absence. We were privileged to gain a grad student, Gabby Conard, and PhD student, Robin Hall, to advise us and provide their knowledge both on the individual robot itself in addition to getting around the lab facilities. They have been extremely helpful in all aspects of this project, from specific technical advice to general work-life balance advice. We greatly appreciate their involvement and guidance throughout the process.

About a month into the school year, we were able to meet with our advisor and establish project direction, as well as finish administrative and organization tasks. However, the delayed start led us to shift our original credit breakdown of ⅓ for A, B & C terms to ⅙, ⅓, ⅓, ⅙ in A, B, C, and D terms respectively. This shift significantly helped us, allowing us to extend our project, but we were still left feeling as though we had not enough time to accomplish all we needed to with the available resources and pressures of deadlines.

Furthermore, we were met with supply chain issues in addition to poor-functioning machinery. As a result, we spent extensive time troubleshooting and repairing machines so that we could print our already delayed parts. We encourage future teams to take proper care of the machines, in addition to encouraging others to do so.

7. Conclusions + Recommendations

The first iteration of the CLARA pipe inspection semi-rigid robot was a good proof of concept, demonstrating that the origami inspired salamander robot developed in the WPI SRL, or Soft Robotics Lab, could be reduced in size to fit within regulation pipes found in pipe networks. The project work resulted in a functioning prototype robot capable of traversal in a pipe controlled wirelessly over WiFi signal. It featured novel work on smart motor driver boards which allowed for control of motors in a small package, as well as a new expansion and contraction linkage mechanism to increase or decrease the diameter of the triangular wheel segments.

This iteration of the project focused on taking the work done by the previous team and expanding upon it, working to make a more complete platform suited for exploration or inspection of pipe networks, as well as future research into the possibilities of a robot of this nature. General casing improvements increased robustness and protection from external damage, as well introduced a slimmer and more consistent body profile to the robot for a more finished look. A new winch module rectified design flaws in the previous iteration which caused unnecessary wear on essential robot components. A modified wheel module allowed for active modulation of a passive suspension linkage to provide constant pressure to the inside surface of a pipe, as well as be unhindered by unexpected changes in pipe diameter. Duplication of this driven wheel segment provided the ability for the robot to be moved by both ends, allowing for proper maneuverability through junctions and the ability to maintain grip through gaps in normal pipe topology. And a new camera module provided feedback to the operator and allowed for true inspection of pipes as well as steering information. These improvements, as well as those not mentioned, represent a marked improvement upon the previous years work, and we believe it provides a valuable platform with great potential. However, throughout the project, we have not only identified many possible areas of future research to expand upon this work, but also many areas of possible work for improvement upon the work done this year.

7.1 Future Project Work

Following the conclusion of this iteration of the CLARA robot, there are many avenues for potential expansion and improvement. These include changes to the existing mechanical, electrical, and software systems implemented throughout the robot, as well as introduction of new modules and systems which would further expand the functionality of the robot.

With regard to changing the existing systems, there are a few areas in which this iteration was not quite able to improve as much as we had hoped, and that we believe would be good focus areas for future project groups. First, the overall length of the body following our modifications was not particularly harmful, but a shorter length could potentially help maneuverability. Second, further exploration of the possible varieties of wheels could identify tires with even better grip than those designed for this iteration. Furthermore, expansion upon the design of the wheel segments to possibly include more wheels, i.e. four wheels per segment rather than three, could expand the possible reach of the robot, allowing it to explore small crawl spaces or ventilation ducts as well as pipe networks. Third, a ring light could be attached to aid in the vision of the camera sensor, or other low-light sensors such as night vision or infrared cameras could be implemented. We recommend that the exact needs of data from pipe inspections be researched and taken into account during the decision making process for which sensors be used in future.

Expanding upon the robot, there are many avenues of *new* research and development which could be taken to improve upon the robot's overall functionality. First, research could be done into possible payloads, along with a deployment mechanism to attach to and detach from the robot while in a pipe network. Possible payloads could be water sample collection, tracking devices, etc. Secondly, a major possible expansion could be the development of a universal module connection interface. This would be a connector design that remained consistent throughout each module, transmitting I2C signals and power between each segment of the robot and allowing for modular swapping of wheel segments, sensor packages, and future modules which would be developed. This would vastly increase the number of module types that could be developed and facilitate development of these modules without needing to recreate the platform, overall increasing the number of possible applications this robot could have. Third, we suggest that future groups work to fully waterproof the robot, taking advantage of the consistent body profile to potentially produce a silicone sleeve or other protective measures to ensure that the robot suffers no damage due to the moisture in pipe network environments.

7.2 Advice and Recommendations

Beyond suggestions for future development of the robot, we have some general advice we would like to leave behind for any future project or development teams. These include things we learned during our time with this project which we believe would help facilitate the research and development process within the SRL.

First, be smart about your 3D prints. Make sure to consider tolerances in your designs, as well as print orientation, support placement, and print resolution. Additionally, if printing in resin, clean your prints thoroughly. We suggest running a few cycles in the FormWash, as well as some manual 'swishing' in a bath of IPA if possible. Otherwise, additional resin will cure inside the small spaces of your parts and potentially render them unusable.

Second, allow yourself plenty of time should you need to cut and fold another Yoshimura origami module. Once you determine the general process of folding, it gets quicker and easier, but the connection of the individual pieces is difficult and takes a lot of time.

Third, order parts *well* ahead of time. Shipping delays can cause you a lot of headaches if you aren't careful, especially when ordering through the official channels like the RBE part order forms. If you need a part as soon as possible, you *may be* better off ordering it yourself and submitting an expense report at the end of the term with any personal funds you have spent. Just be sure to save your receipts or invoices, and don't go over your budget.

Finally, document as much of your process as you can, and stay as organized as you can. You will be generating a significant amount of data and files over the course of your project, and if you aren't careful you will lose things you need down the road. Don't throw away anything, and don't put anything where you won't be able to find it when you need it. It sounds obvious, but even the smallest most insignificant seeming things could be exactly what you are looking for later on.

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