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Developing a Marking Arm for Autonomous Cable Detection

A Major Qualifying Project Report
Submitted to the Faculty of Worcester Polytechnic Institute
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Degree of Bachelor of Science

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Abstract

Underground utility marking is a task that is labor-intensive, repetitive, and in some cases dangerous. In the New England area, utility providers fund the Dig Safe nonprofit which provides this service for free. The operating costs of this service are almost entirely in labor and transport as opposed to consumables. As a result, our sponsor, Eversource, has expressed interest in using semi-autonomous robots to speed up the scanning and marking process. Dig Safe and similar nationwide organizations are also often required to operate next to active roadways, presenting a major safety hazard to their workers.(WITN, 2020) Due to these factors, Eversource has sponsored WPI to create a robot capable of detecting and marking utilities, specializing in the simple but dangerous cables located near or under roads. Previous teams have created 3 iterations of a 2-DOF marking arm on the back of the robot, however this arm had several issues that led to the decision to completely redesign it. These redesigns focused on decreasing its weight, increasing its rigidity, and replacing over- and under-specified mechanical parts with strong, lightweight alternatives.

Background

Before digging more than a few inches into the ground, MA residents are required to contact Dig Safe, a mapping and marking organization funded and operated by several utility companies, including this project's sponsor Eversource. Eversource commissioned this project several years ago to help resolve safety and financial issues faced with Dig Safe. Utility workers working in or near streets are often injured or killed by traffic, even while following safety precautions. (WITN 2020) Eversource workers have similarly been hit by vehicles, including one such event in 2020. (Saccone, 2020) The cost of labor when responding to every single ticket (as required) in and around Massachusetts also presents a major issue to Eversource, especially given the risks presented to workers. Much of the marking is or around streets, where elevation changes are predictable and obstacles are minimized. Given both of these issues, cable detection and marking is an ideal field to partially automate. Robots can do work in and around streets where they can navigate easily, while humans keep an eye on the robots and handle detection and marking around and over hedges, fences, gardens, and other barriers that would impede the robot. The scope of this ongoing project is to develop a robot that can autonomously navigate to expected cable locations using company-provided rough maps, detect and follow cables using an AC cable detector, mark the observed location of the cable using paint, and optionally save the detected cable's position and parameters for later use updating the maps. As of the start of this semester the robot had serious noise issues preventing it from detecting cables and mechanical trouble with the marking arm preventing it from painting marks. The goal for the end of this academic year (May 2023) is to demonstrate full capability to locate, track, and mark cables, meaning the marking arm needed to be repaired or fully redesigned. Due to the serious damage on the current design it was decided that a full redesign was the best option.

Arm Requirements

Our robot is required to make a specified pattern on the ground every 10-50 feet to denote an underground cable. This pattern, specified by Eversource, denotes an electrical cable underground, and is to be approximately 18" wide to match Eversource's existing standards.

Figure 1: Example “IOI” Mark

The robot needs to be able to make this mark on surfaces of varying smoothness and height, and the marking operation needs to be performed in a manner that does not require the robot to reposition itself beforehand. This required an arm that has high fixed ground clearance (8-10”) or can vary its height in order to paint on top of curbs, sidewalks, or siding. It also needs to be able to paint ground-level surfaces when the robot itself is elevated or inclined.

Figure 2: Example Cable Mark on Varying Terrain

Previous Arm Designs

Actuation

The 2020-2021 team constructed a 2-DOF arm attached to the back of the robot to meet the specified reach and clearance requirements. The arm, using a modified SCARA configuration, had a wide reachable workspace of a roughly 18” radius semicircle on the back of the robot, and was roughly 8” off of the ground. Thus, the arm had the reach and clearance to paint the required pattern even when it is off-center or at a different height than the robot, for example if the robot is at street level and the mark needs to be placed above a curb. This core mechanical layout has been in use for all 4 iterations of the arm including this semester’s redesign. The implementation of this concept has varied across all 4 versions.

Version 1: 2020-2021 Team

The first version of the arm had slightly modified size and mounting requirements, as it was intended to mount to a Husky UGV chassis. Since the entire robot was much shorter than the current one, the arm was mounted to the top plate of the robot, but still reaching over the back side. It used much smaller and lighter motors than all future iterations, with 2 Pololu 50:1 gearmotors powering it. These were located at the shoulder and elbow joints, and directly powered the 2 stages of the arm.

Figure 3: 2021 Arm

(Weiner et. al., 2021)

This arm was able to demonstrate initial operability, however it had underpowered motors and supported the heavy can of paint at the end. The 2021-22 team noticed some structural issues as a result of mechanical stresses inside the joints, and so designed 2 iterations of the arm to rectify them, as well as to allow faster operation.

Versions 2-3: 2021-2022 Team

Iterations 2 and 3 had nearly-identical arm designs, although the whole arm was reprinted for iteration 3. The arm was extended in these versions to allow roughly a 24” radius workspace. Both iterations moved the paint can off of the arm, instead mounting it to the top of the robot. This lightened the arm by up to up to a pound depending on how full the can was. The 2nd stage actuation motor was also moved off of the arm, allowing much heavier and more powerful stepper motors to be used. The new design had the 2nd stage motor placed directly above the 1st stage joint, with its axle protruding down through the bearings supporting the first stage to a belt pulley inside the arm. This first pulley was connected to a second one within the 2nd stage joint using a timing belt. The 1st stage motor was offset to the side, rotating the 1st stage using a large 3d-printed gear. To reduce response times in the paint mechanism, a servo-actuated aquarium valve was placed at the end of the tube at the tip of the arm, allowing the can’s valve to be left open and all of the flow control to be handled at the end effector.

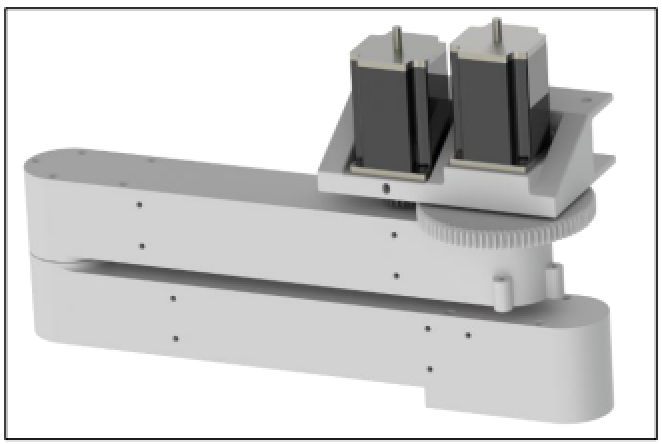

Figure 4: CAD Model of 2022 Arm

(Mitchell et. al. 2022)

The second iteration of the arm, while mechanically an improvement over the first version, had several mechanical issues that prevented it from working in our tests. The first of these major issues was that the arm was considerably heavier than it needed to be. Each of its joints had a stack of several axial and radial bearings that were over-toleranced for their role in supporting the arm, with the radial load bearings being rated for over 1000lbf when the moving parts of the arm weighed roughly 5lb.

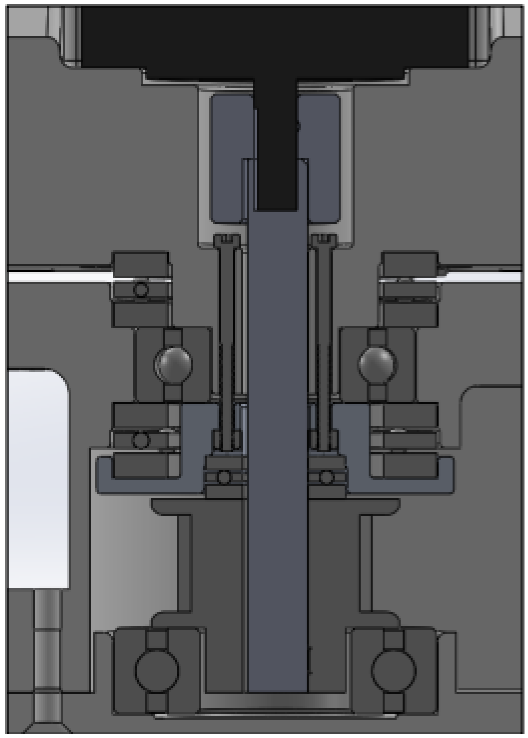

Figure 5: Cutaway Section of Arm Joint 1

(Mitchell et. al. 2022)

This unnecessary weight meant the arm movement had to be much slower than it otherwise could have been. Another over-engineered mechanism was the belt and pulley system that actuates the 2nd stage. It used wide-pitch timing belts, whose wide tooth distance meant that there was considerable looseness in the 2nd stage. As a result, the second stage could be manually moved back and forth roughly 30 degrees even with its motor stationary. This was partially due to the wide pitch and partially due to the fact that the belt was not fully tensioned, with no way to do so.

The final major issue with this iteration was that the 3d-printed plastic of its structure was cracking under stress. We believe this is largely due to the weight of the bearings and hollow shaft for the 2nd stage, as well as the valve and its metal-gear servo located at the tip. The cracking we noticed was in 2 primary areas. The first of these areas was the surface of the 1st stage gear, which was splitting in several areas. These cracks caused the teeth to shift slightly (adding friction to the gear's motion) and also caused protrusions that directly caught on the stationary part above the gear.

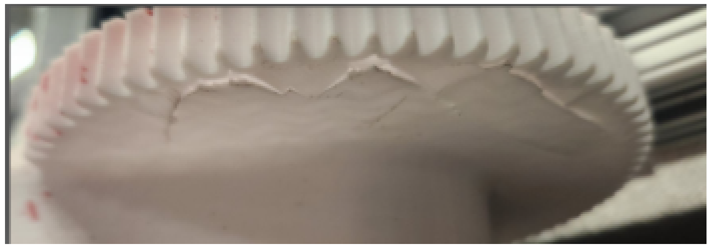

Figure 6: Cracking on Surface of Arm Stage 1 Gear

This deformation in the gears resulted in inconsistent, jerky motion of the arm when in motion. The other area we noticed cracking was in the structure of the 1st stage, where cracks were expanding from the bolts used to assemble it. Due to redundancies in these bolts there wasn't a major structural failure yet, however if we continued using the existing arm we believe these cracks would have continued appearing until it failed.

Marking

We were instructed to use the same paint as Eversource's technicians, a chalk-based paint that washes off of surfaces after a few weeks to months depending on weather conditions. This type of spraypaint is designed to be loaded upside-down into paint "guns," which depress the nozzle (pointing straight down) when a trigger is pulled. This allows the operator to paint with the can near ground level while standing or walking upright, allowing them to mark cables faster and more comfortably.

Iteration 1

The first arm iteration used the same method of marking, with a modified paint gun attached at the tip of the arm. A servo pulled on the gun's trigger cable to activate the can. Due to the minimal modifications from the original COTS paint gun this was a consistent, reliable marking mechanism. However, it placed a much heavier weight at the end of the arm than the other iterations, slowing down the maximum speed of the arm.

Figure 7: COTS Paint Gun

Iteration 2

The second iteration moved the paint can onto the robot's chassis. This was necessary to allow the arm to move faster while using light and inexpensive motors, and also allowed the arm to "nest" (with both links folded inline against the robot) when not in use, making it more compact. A 2mm ID tube intended for compressed air was used to carry paint from the can to the end of the arm, running inside both links. A plastic-geared servo was used to depress the nozzle on the paint to spray it. In testing, the previous team reported that there was a moderate delay between when the can was depressed and when it started to spray. (Michell et. al. 2022, p12) This led them to redesign the paint sprayer again.

Iteration 3

The third iteration was intended to deal with the timing issues to allow painting with consistent start and stop times. A servo-actuated valve was placed at the tip of the arm, allowing the can's servo to depress the can nozzle before the start of a marking and leave it open for the entire time, with the valve at the end starting and stopping the flow. One issue with this design was that the servo at the end still took time to open and close the valve, meaning the spray timing was still slightly off. This is noticeable by looking at their test images, where the end of each marking is wider since the paint continued spraying after the arm stopped. The more critical issue with this iteration was that the valve clogged with dried paint, rendering it inoperable.

Figure 8: Iteration 3 Paint Demo

(Michell et. al. 2022)

Arm Iteration 4

During the Fall 2022 semester, the arm was fully redesigned. The new design focused on weight and rigidity, in order to enable fast, accurate movement. These design goals were focused on because the third iteration previously attached to the robot was unable to move consistently or paint at all. The new carbon-fiber structure and improved hinges solved the motion issues, and reverting to the second iteration's painting strategy with the delay before paint starts flowing being corrected in software is expected to fix the painting issues. The arm reused the existing motors and SCARA configuration from iteration 3 in order to keep costs low and enable the use of the redesigned arm code created this year.

Figure 9: Render of Arm Iteration 4

Actuation

The iteration 3 arm weighed 4lb 10oz, leading to damage to its components and skipping / stalling in its drive motors. One of the main goals of the new design was to bring the weight down as low as possible, in order to allow it to be driven considerably faster without requiring the purchase of more powerful motors / gearboxes. There were 2 main areas of focus when redesigning the arm.

The first area was the structure of the arm itself. The 2” wide square 3d-printed box-frame of both stages was replaced with 5/8" carbon fiber tubing repurposed from a past MQP. The tubing was used to create 2 struts on the first stage connecting the 3d-printed joint bodies, and 1 length of it was used to form the main body of the second stage with a 3d-printed adapter connecting it to the shaft. This led to a lightweight, rigid structure that didn’t suffer from the cracking issues noticed around fasteners on the 3rd iteration. The first stage gears were replaced with a belt to prevent the cracking and interference they noticed on them. The new structure design also included methods to tension both belts, by sliding the first stage motor away from the joint and by sliding the second stage joint farther down the carbon fiber tubes it was mounted to.

The second area of focus was the design of the 2 joints used on the arm. The existing designs used over-redundant and over-specified bearings, using combinations of thrust and radial bearings to support relatively low forces. These added considerable weight to the arm, especially at the second joint where a lightweight design was critical to keep the arm’s moment of inertia low. The new design, while mechanically complicated, lightens the joints considerably by removing redundant bearings and switching to considerably smaller, lighter ones.

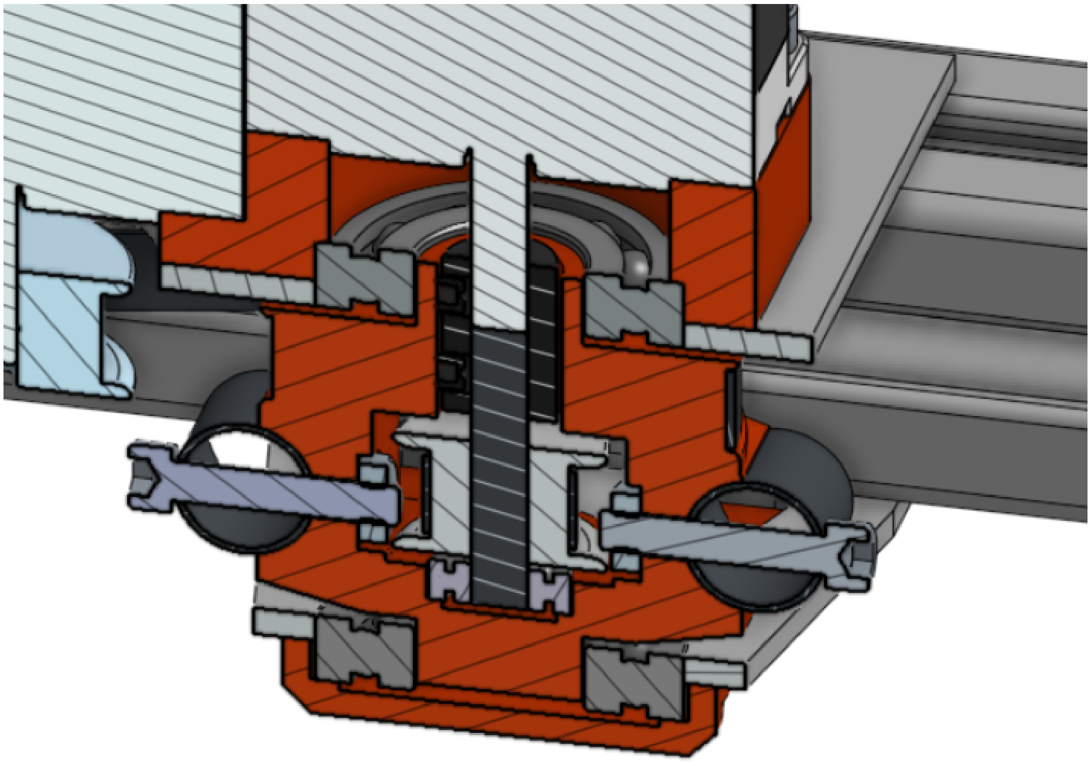

Figure 10: Redesigned Joint 1 (Cutaway)

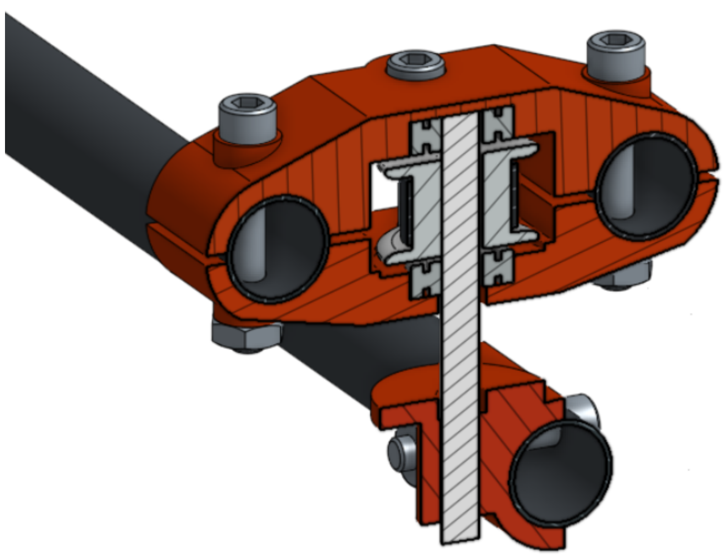

Figure 11: Redesigned Joint 2 (Cutaway)

The shaft for each stage was reduced from 3/8" to 1/4", further reducing the required size for the bearings. The smaller-pitched belts decided on earlier also led to smaller, lighter pulleys being used. These weight reductions combined with the structural redesign and the removal of the servo valve (detailed below) led to the weight of the moving components for the 1st stage being reduced from 44oz to 8.5 oz, and the second stage components being reduced from 30oz to 1.5oz. The total weight reduction was thus from 74oz to 11oz, or 85%.

Marking

At the start of the fall 2022 semester the existing paint assembly was nonfunctional due to major clogging in the valve. Paint (or air) was unable to flow in either direction and the valve was jammed in position. It was unclear if the valve was in the open or closed position, as attempts to force it to rotate by hand stripped the shaft. To continue using a valve, either a clog-proof mechanism or a method of purging the tube after painting was complete was needed. It was unclear what (if any) valve type was immune to paint clogging and a purge system would add significant mechanical complexity, so the valve mechanism was removed. The reason this option was taken was due to the redesigned arm code. The new program generates polynomial paths for the arm, where the time since the start of the movement can be passed into a set of polynomial expressions with constants calculated ahead of time to get the set angles for both joints at a given time. Because the setpoints are open loop and time-based, a simple solution to the delay between triggering the can and paint flowing out of the nozzle can be circumvented by offsetting the time passed into the polynomials by a determined set amount. This should result in near-perfect timing for the painting while leaving the arm design simple and light. The existing can holder did not present any design issues so it was reused in its original configuration, although its servo was completely unresponsive so it was replaced with a working one.

Design Phase

Late in A-Term, another MQP (designing a hexacopter) discarded an assortment of carbon-fiber parts used on a previous design. These parts included 6 5/8"tubes that were completely unmodified, as the drone parts had clamped to the outside. These were picked up by the current team and it was decided to retain them for potential future use on the arm. Due to their high rigidity and perfect sizing for the task at hand they were selected for use in the design. The CAD platform Onshape was used to design the arm, as it automatically synchronized between devices, has integrated version control, and contains a parametric feature library allowing fastener hardware to be quickly integrated into designs. The design took a few iterations, as the entire first joint had to be completely redesigned to prevent a potential bending issue that would lead to friction on the second stage pulley.

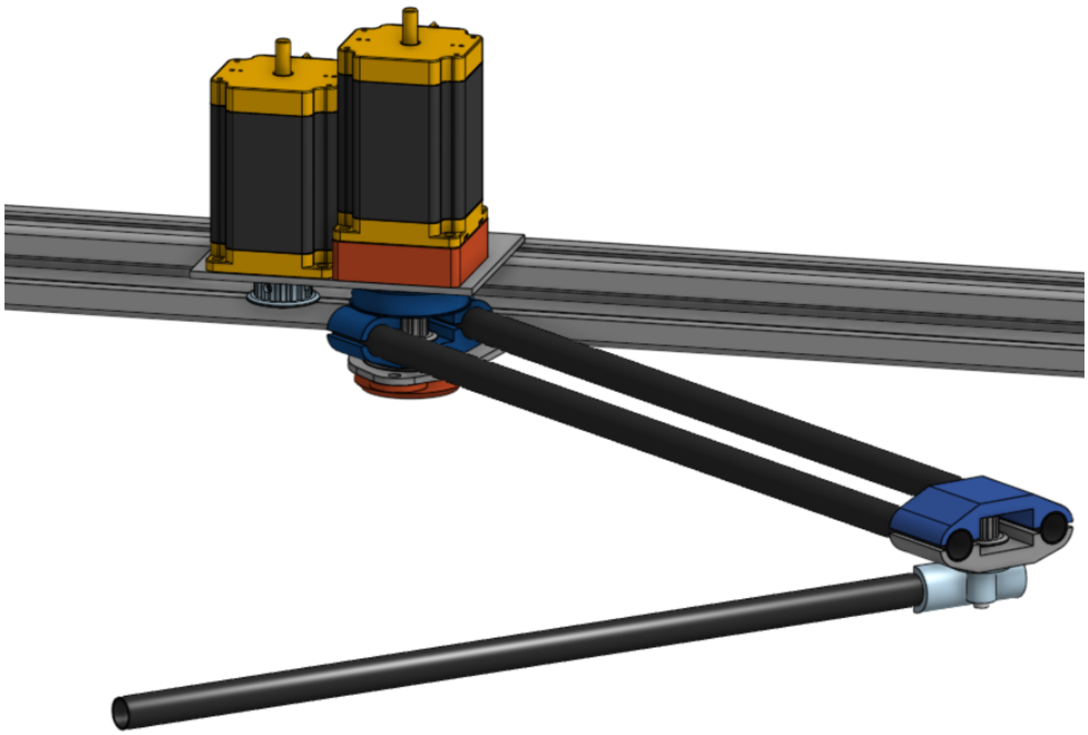

Figure 12: Early Arm Design

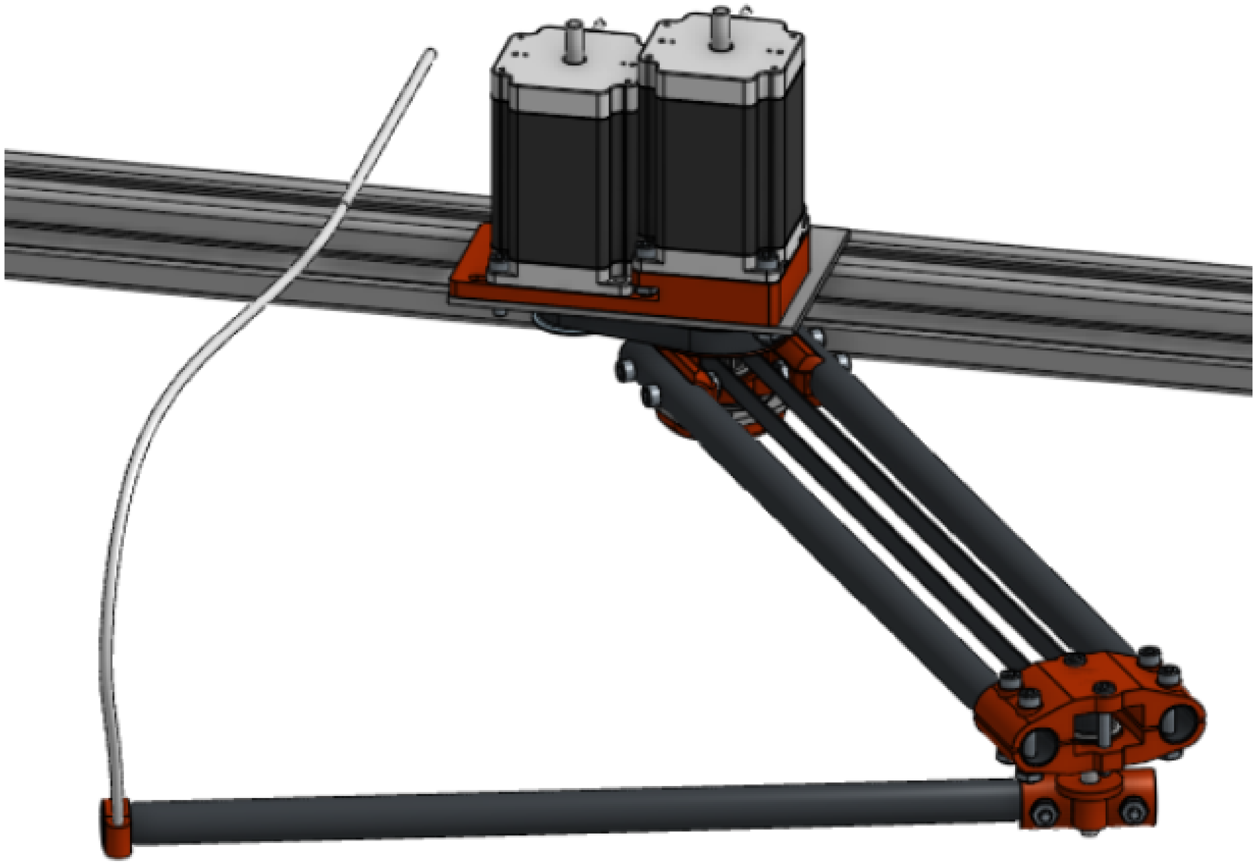

Figure 13: Finalized Arm Design

Assembly

Assembly proceeded as expected. Major clearance problems were noticed afterwards between the bolts that attached the carbon fiber tubes to the first joint and the aluminum extrusion rail that the entire arm was mounted to. The optimal fix to this would be to order extended aluminum plates from SendCutSend that moved the entire arm approximately 1/2" farther from the rail. Due to time constraints it was instead decided to develop a workaround. The workaround that was used was to switch the #10-32 hardware that attached the tubes to the first joint with M5 bolts and nuts, which were shorter and had button heads that could fit fully within the tube. Although difficult to insert, these new bolts no longer collided with the extrusion. There was still a minor amount of drag caused by the tubes themselves dragging on the rail at either end of the arm's movement, but this was low enough for the motor to easily overpower. There were also issues noticed with the belt tensioning for the second stage, with the plastic parts clamping onto the tubes bending, pressing against the pulley, and sliding towards the base reducing the tension. A temporary workaround (2 shaft collars on the tube) is in place while a more permanent solution (redesigned parts that clamp using bolts passing through the tube) is developed.

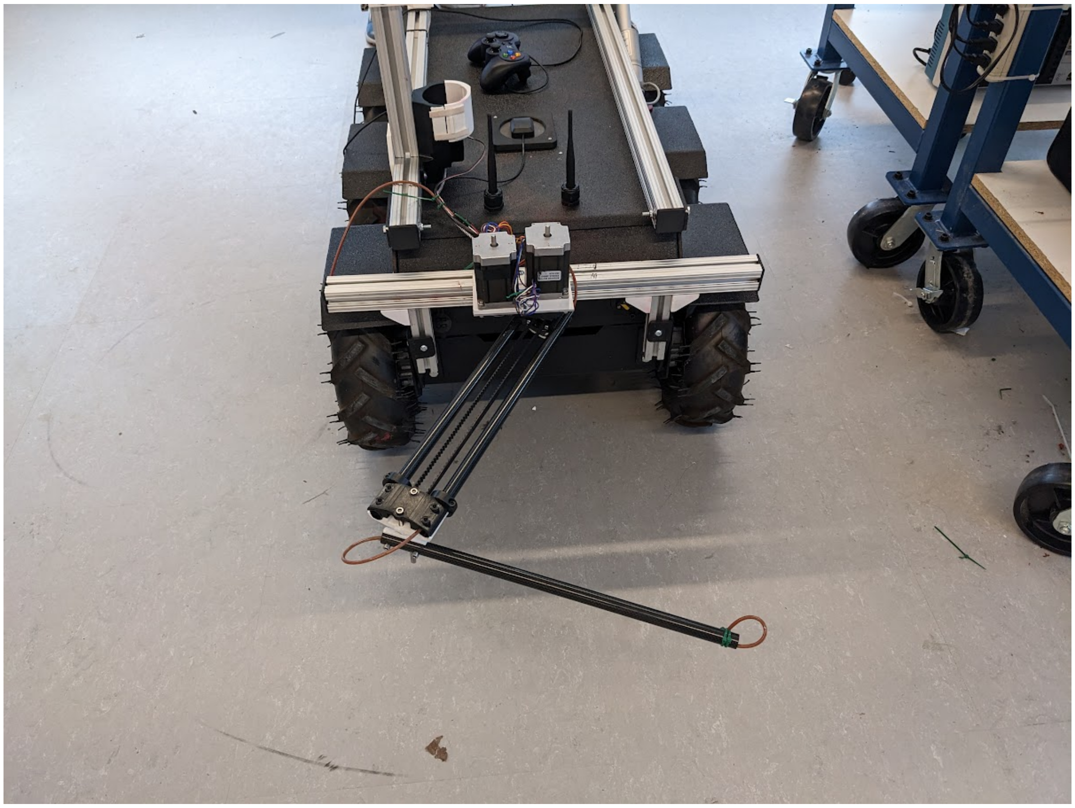

Figure 14: Assembled Arm

Testing

Testing of the new arm was accomplished. Mechanical testing showed that the arm is sturdy and well-tensioned, although minor axial twisting was noticed in the first stage due to the clamping issues. Holding both motor shafts in place locks the arm in position rigidly. Tests of the code rewritten by another project member showed that both arm sections could be moved by the motors, however electrical issues currently being investigated caused it to overshoot in many of its movements. The stepper driver used on the second stage motor currently only runs the motor in one direction for unknown reasons. A fix for these problems (a spare stepper driver board off of one team member's 3d printer) should be implemented early in the spring. While the arm was not able to be demonstrated moving to setpoints (and thus could not be shown painting the example mark), it is mechanically capable of doing so and should be able to show full functionality once the electrical issues are resolved. One of the tests ended with the motor attempting to drive the arm past its hard stop, leading to the motor stalling and subsequently skipping steps. The arm was undamaged by this meaning it is able to survive strong impacts and other unintended mechanical stresses.

Conclusion

The redesigned arm fixes the mechanical issues found in all three previous iterations. It is stronger, lighter, and can be driven faster than any of its predecessors, and thus should be usable without further major design changes through the end of the Dig Safe project. While problems with existing electronics prevented it from being demonstrated by the end of B-Term, the resolution of those problems should be the last step in showing full, consistent operability of the paint arm. As one of the two major remaining sections of the project that required completion as of this semester, the new arm brings the project much closer to final demonstrability.

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