2023 Robotic Arm Mechanical Design

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1. Introduction

The purpose of this report is to document the various design decisions for the robotic arm to be used in the 2023 CIRC. The robotic arm is the rover's primary method of manipulating the environment around it. For CIRC 2023, the tasks that require the use of the arm include Water Redirection, Arm Dexterity, and Land Speculation & Prospecting. The robotic arm has 5 degrees of freedom and is designed to be lightweight and robust. A budget of $2,000 is used.

2. Background

The previous prototype arm was made of laser-cut wood and used linear actuators. Although linear actuators can provide a lot of force, they are far too heavy. The previous arm, designed by Lawrence Wong, weighed about 15.9kg. The robotic arm weight is critical as it shifts the rover's center of mass towards the front. This could lead to unstable conditions as the rover is decelerating or descending a steep hill. After a few design iterations, a 5-axis arm made of PETG, carbon fiber, and aluminum was designed for CIRC 2023.

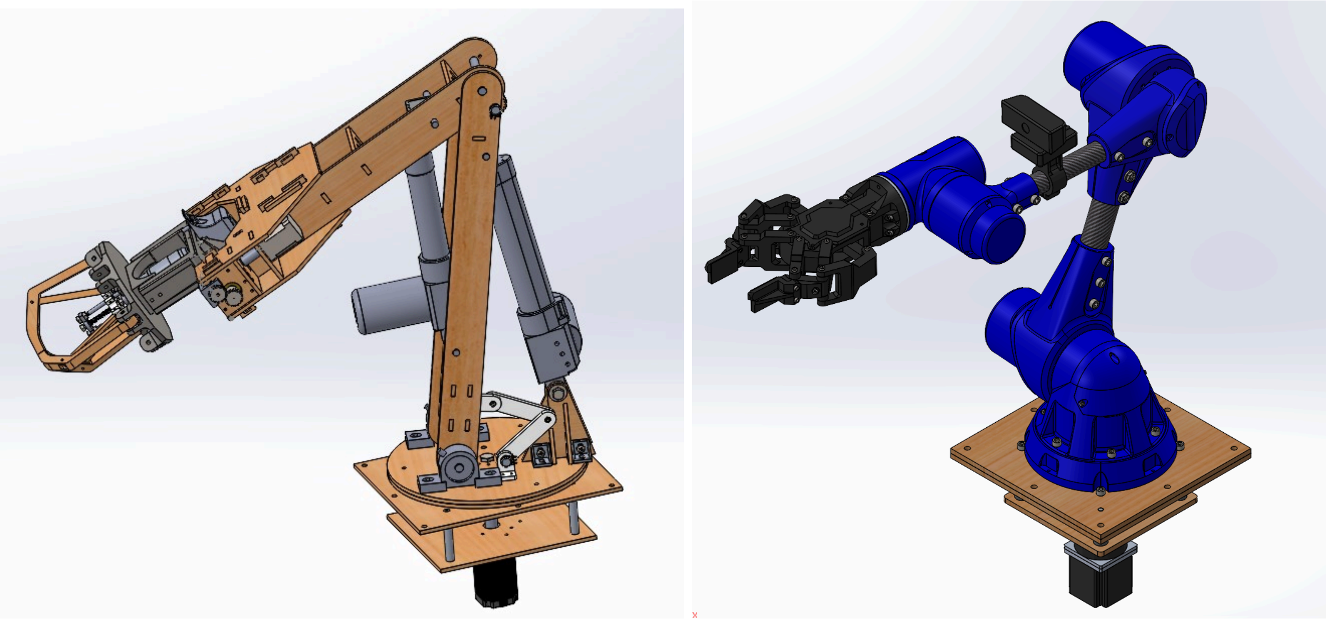

Figure 1 - Wooden prototype arm (left) vs. CIRC 2023 arm (right)

3. Objectives

The main design objectives are the following:

1. **Weight** - The arm should weigh less than 10kg in total
2. **Maximum Payload** - It must be able to pick up a 2kg object
3. **Precision** - The arm must be precise enough to pick up objects as small as 1cm without difficulty

4. Linkage Model

The first step was to determine the desired lengths of the links for the arm. This was done with a SolidWorks sketch. Two main things needed to be tested with the sketch, the horizontal movement range of the gripper along the ground, and the vertical movement range along a wall. Approximate ranges of effective movement were tested in the SolidWorks sketch and shown in Table 1 below. Figures 1 and 2 show the robotic arm sketch in its different configurations.

Table 1 - Effective Movement Range of Arm

Link 1 Length [m]	0.32
Link 2 Length [m]	0.29
Gripper Length [m]	0.27
Horizontal Range (along ground)	0 - 0.42m
Vertical Range (along wall 0.5m from rover)	0.13m - 1.1m

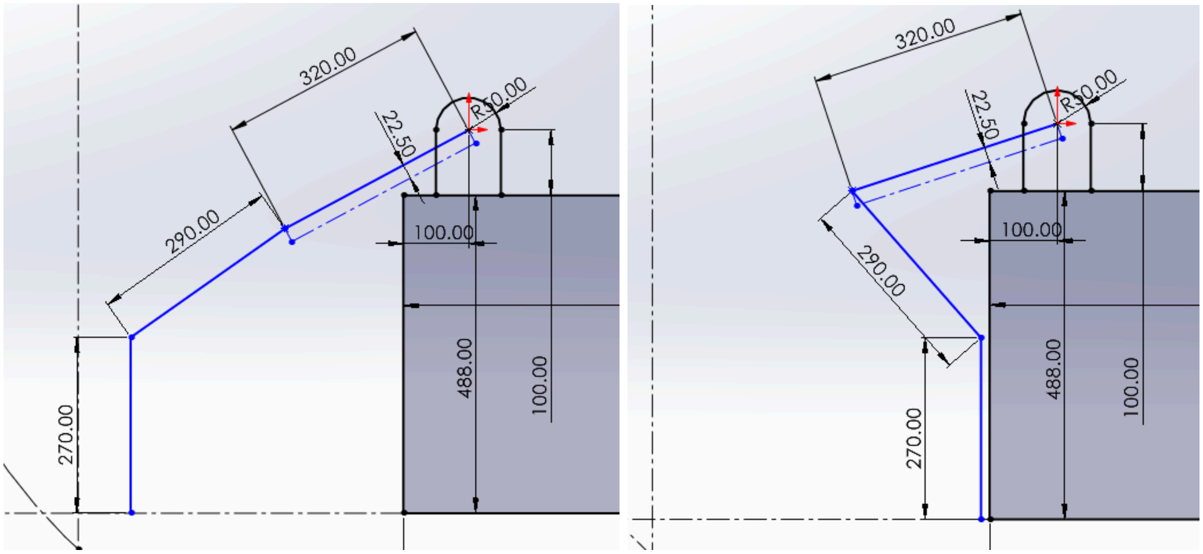

Figure 2 - Horizontal Movement

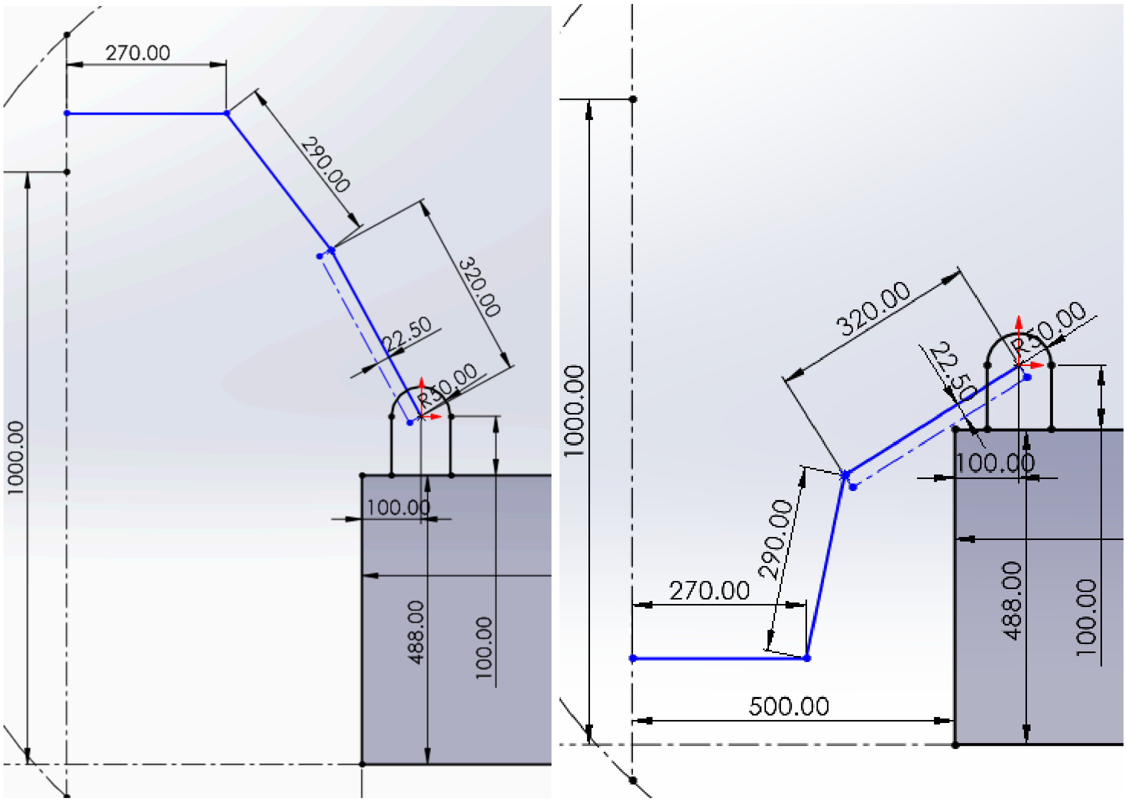

Figure 3 - Vertical Movement

5. Motor Selection

Three main criteria are used to determine the appropriate motors at each joint: torque, speed, and inertia ratio. This torque calculator: Robotic Arm Torque Calculator was used to determine the required torque at each joint. The calculator assumes point masses at each joint and a constant angular acceleration in a fully extended arm position (worst-case scenario). The static torque shows the required torque to keep the arm in the desired position while the dynamic torque adds the inertial forces due to constant acceleration.

Table 1 - Torque Calculator

Parameters			**Static Torque**	**Nm**
1st Link Length [m]	0.32		Shoulder joint Torque	33.90
2nd Link Length [m]	0.29		Elbow Joint Torque	16.68
Gripper Length [m]	0.27		Wrist Joint Torque	5.76
1st Link Mass [kg]	0.152			
2nd Link Mass [kg]	0.141		**Dynamic Torque**	**Nm**
Gripper Mass [kg]	0.35		Shoulder joint Torque	38.82
Elbow Joint Mass [kg]	1.5		Elbow Joint Torque	18.01
Wrist Joint Mass [kg]	1.42		Wrist Joint Torque	6.07

Payload [kg]	2.00		Base Joint Torque	3.129
Angular Acceleration [rad/s^2]	1			
Base Joint Mass [kg]	2.1			
Shoulder Joint Mass [kg]	1.5		**Total Arm Mass [kg]**	7.16
Moment of Inertia about Base Axis [kg m^2]	3.13			

The operating speed of each joint should be quite low, between 15-30rpm (ballpark) which is semi pre-determined by the fact that anything faster may cause safety concerns. The inertia ratio is defined by the reflected load inertia divided by the rotor inertia. Generally, an inertia ratio over 20 could introduce control instability [1] [2]. Table 2 below shows the inertia ratios for each joint motor.

Table 2 - Inertia Matching for each Joint

	Base **J1**	Shoulder **J2**	Elbow **J3**	Wrist J4	Wrist J5
Gear ratio	100	80	50	50	50
Rotor Inertia (kgm^2)	0.000044	0.000069	0.000069	0.0000077	0.000004
Load Inertia (kgm^2)	7.5	7.4	1.93	0.33	0.05
Reflected Inertia (kgm^2)	0.00075	0.00116	0.00077	0.00013	0.00002
Inertia Ratio	17.05	16.76	11.19	17.14	5.00

6. Mechanical Design

Links

Three materials were considered for the arm links: aluminum, carbon fiber, and ABS pipe. Round tubes were chosen as the cross-section to maximize the moment of inertia efficiency. Square tubes would also be a suitable alternative for easier fastening. Although the cross-section of square tube is slightly more inefficient, the overall change in mass of the arm would be less than 1%. ABS was discarded as a potential material due to its low rigidity. A linkage material with low rigidity would result in higher deflections at the end effector.

Table 3 - Material Properties of Aluminum 6061, Carbon Fiber, and ABS

	Density (g/cm^3)	**Young's Modulus (GPa)**	**Yield Strength (MPa)**
Aluminum 6061	2.7	70	270
Carbon Fiber	1.8	200	2000
ABS	1	1 - 2.65	40

The next option that was examined was aluminum tube since it is widely available, cheap and easy to machine. The tube diameter and thickness were optimized, the full analysis can be found here: Linkage Calculations.xlsx . The goal is to maximize the cross-sectional moment of inertia which lowers the tube mass while maintaining a high FOS. The tube sizes were selected based on deflection, safety factor, and mass (Table 2).

Table 4 - Optimal Tube Diameters and Thickness for Al-6061

Applied Moment [Nm]	Mass/length [kg/m]	FS	Deflection [mm]	OD [in]	Thickness [in]
39	0.599	11.276	0.190	1.75	0.065
17	0.422	12.616	0.545	1.25	0.065

Finally, carbon fiber was examined. Carbon fiber is lighter, stronger, and more rigid than aluminum, making it the ideal material for the links. Applying the same loads, the safety factors and deflections are computed as shown in the table below.

Table 5 - Optimal Tube Diameters and Thickness for Carbon Fiber

Applied Moment [Nm]	Mass/length [kg/m]	FS	Deflection [mm]	OD [mm]	Thickness [mm]
39	0.317	47.396	0.192	30	1
17	0.249	66.134	0.172	24	1

Carbon fiber was used for the links due to higher safety factors and lighter weight. Cheap tubes were purchased on Aliexpress.

Joint Design

The materials for the joints are primarily determined by the manufacturing methods available: 3D printing and conventional machining. With 3D printing, only PETG was considered. PLA was quickly dismissed as an option due to its low glass transition temperature (50C). Higher-performance materials like CF nylon, ASA, Polycarbonate, and CF PEEK would be expensive and hard to print with.

Ideally, a machined joint would be made of Al 6061 due to its lightweight and machinability. An FEA simulation was done in SolidWorks to approximate the end effector deflection for the aluminum joints, the simulation report can be found here. Due to time constraints, we could not machine the aluminum joints.

The CAD assembly files for the robotic arm with aluminum and PETG joints can be found below. Download the zip file and unzip the package on your local computer.

PETG robotic arm: "*ASSY V5, ROBOTIC ARM, 2023*"

Aluminum robotic arm: "*ASSY, ROBOTIC ARM 2024, ALUMINUM DESIGN*"

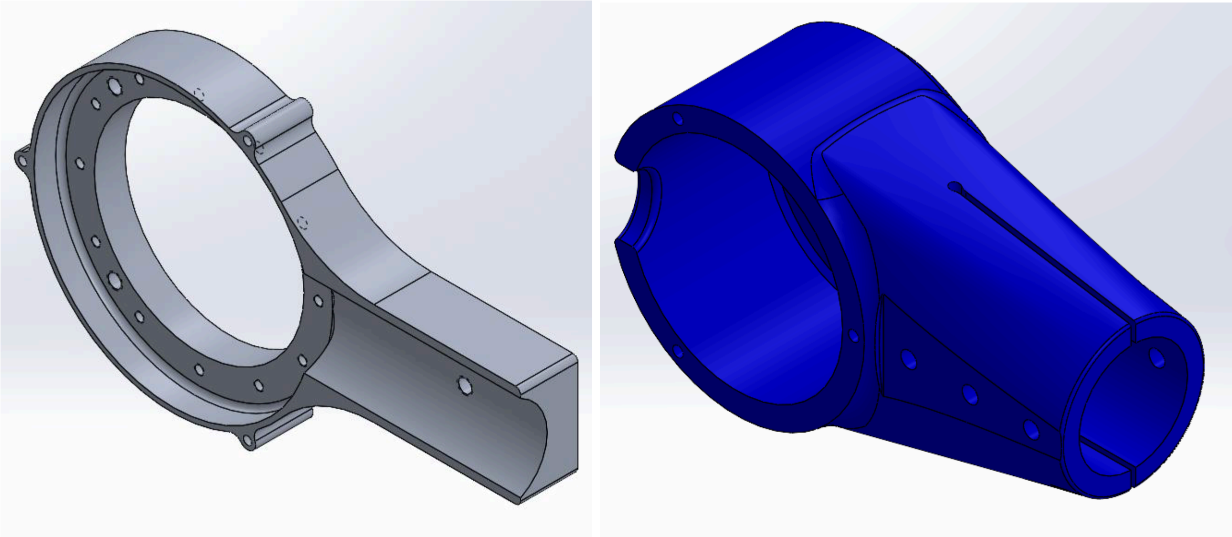

Figure 4 - Aluminum vs PETG joint

Overall, the PETG joints perform reasonably well. One of the main concerns was its low rigidity and strength. A few test prints were done to assess these metrics. The infill percentage was increased around the bolt holes using support blockers in Cura.

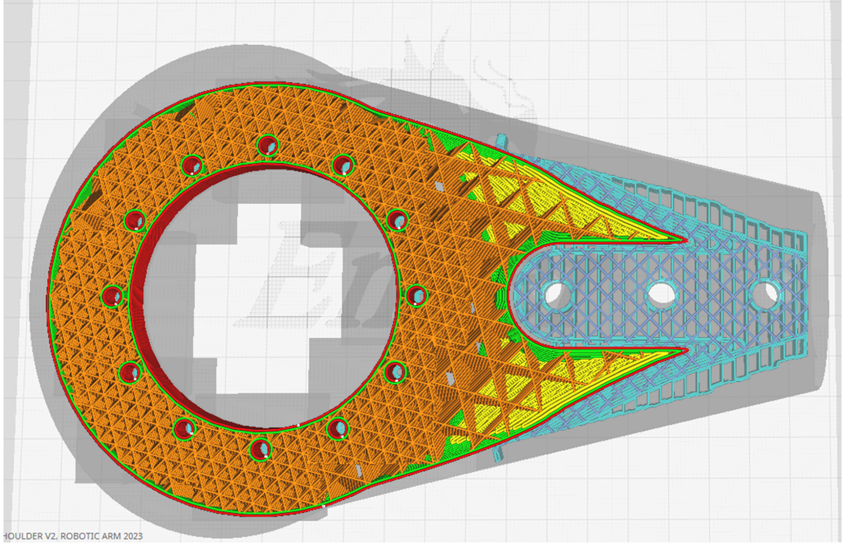

Figure 5 - 50% infill around bolt holes

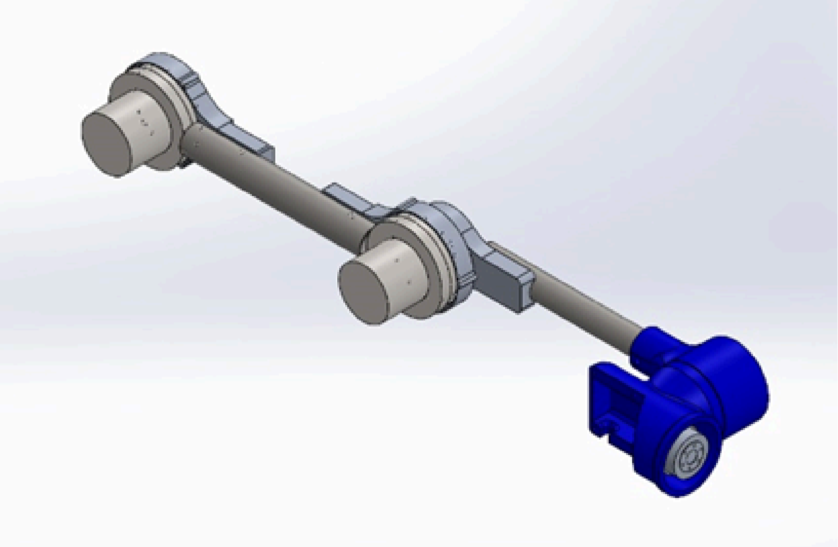

Figure 6 - FEA Simplified Assembly for aluminum joint arm

Base

The motor that actuates J1 is a NEMA 23 stepper motor with a 100:1 gear head. A post and plate method was used for mounting. A custom aluminum shaft coupler was machined to couple the motor shaft to the inner race of the base bearing.

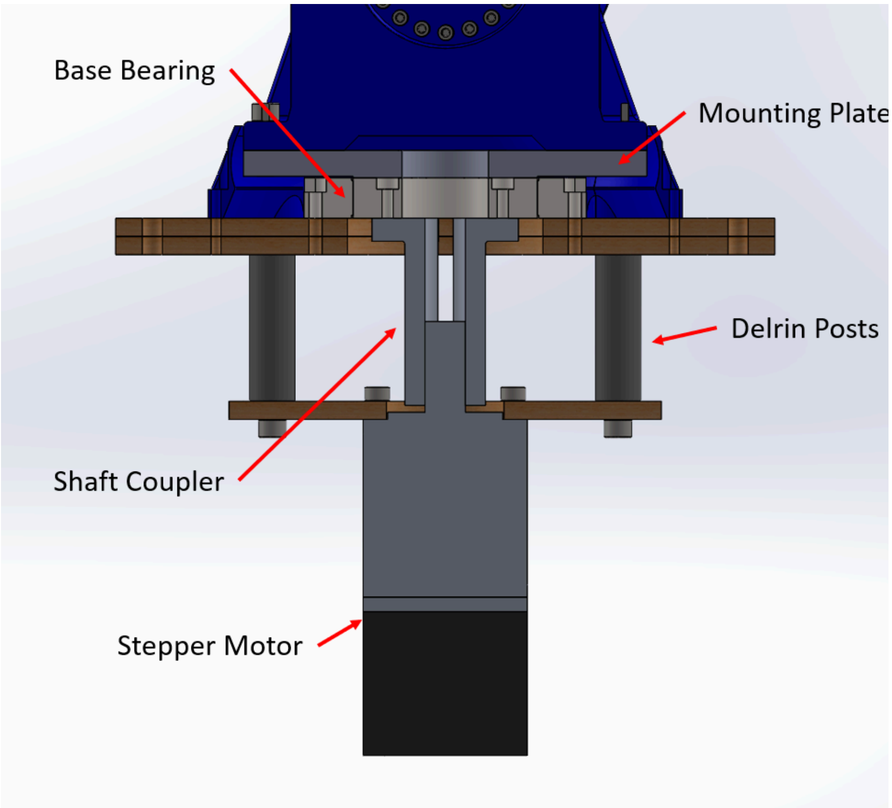

Figure 7 - Base assembly cross-section

Wrist

The wrist motors that actuate J4 and J5 are both NEMA 17 stepper motors. Both are equipped with 50:1 harmonic gearheads supplied by [Harmonic Drive.]() The joints are 3D printed from PETG. A plate is machined from Al 5052 to mount the gripper.

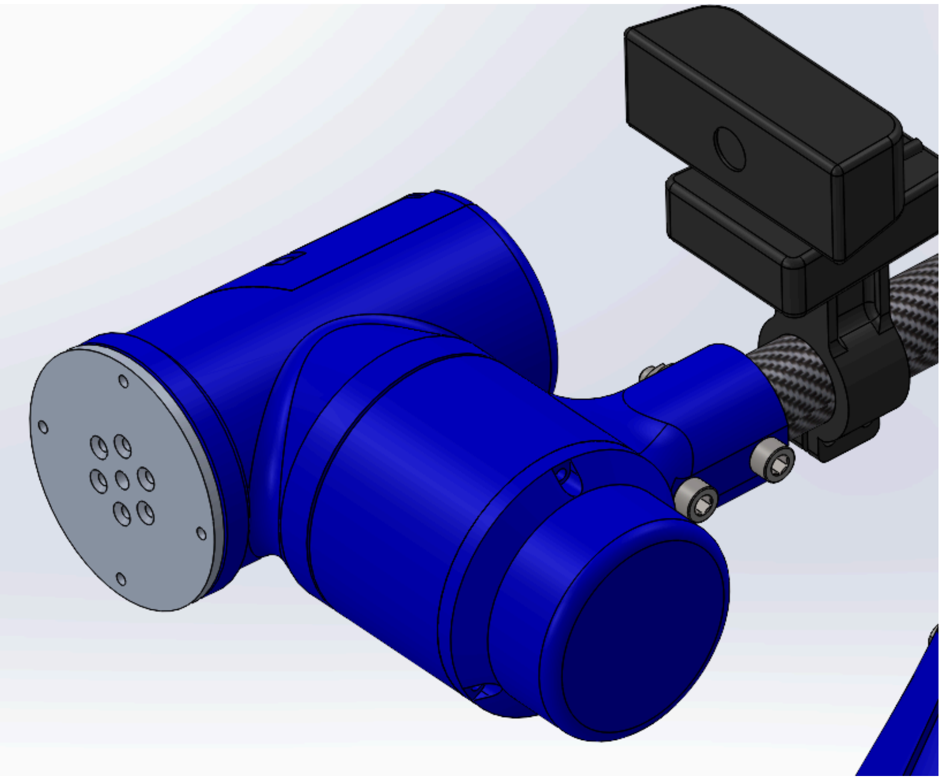

Figure 8 - Wrist Assembly

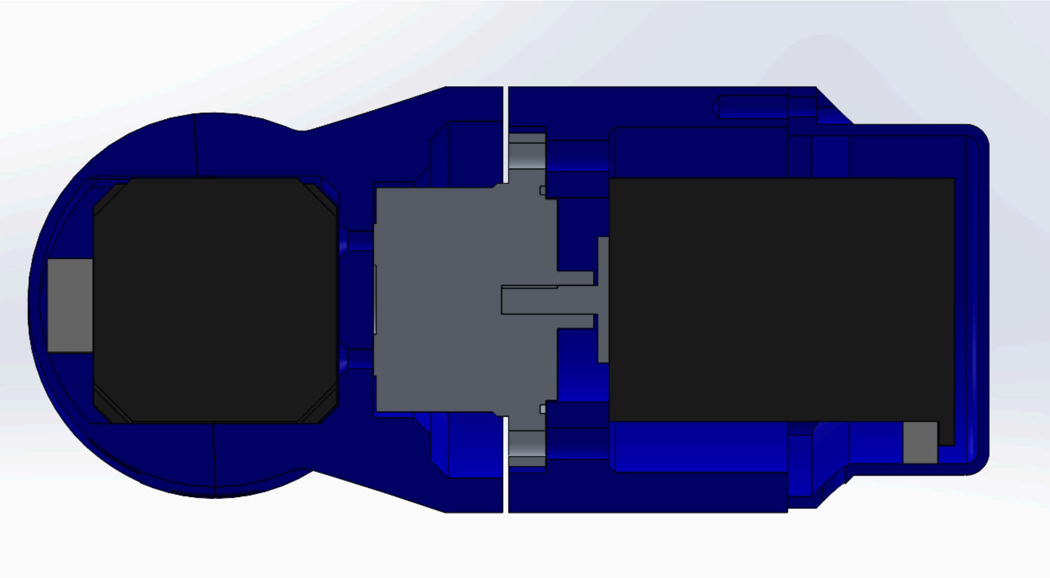

Figure 9 - J4 cross-section

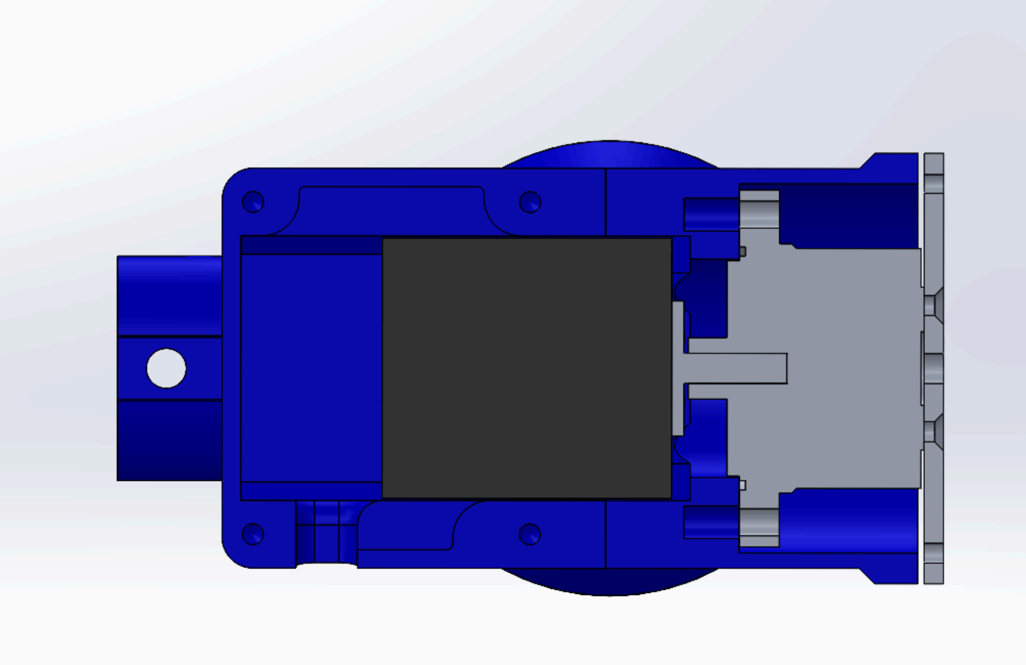

Figure 10 - J5 cross-section

Gripper

The gripper is actuated by a 12V linear actuator. It weighs 373 grams and has a grip force of 32N. The links are printed from CF Nylon and the housing and mount are printed from PETG. The fingertips can be switched to provide a more suitable manipulation method for the desired task (small, pipe gripper, soil claw).

A more detailed process on the linkage design can be accessed here: Gripper Design 2023.

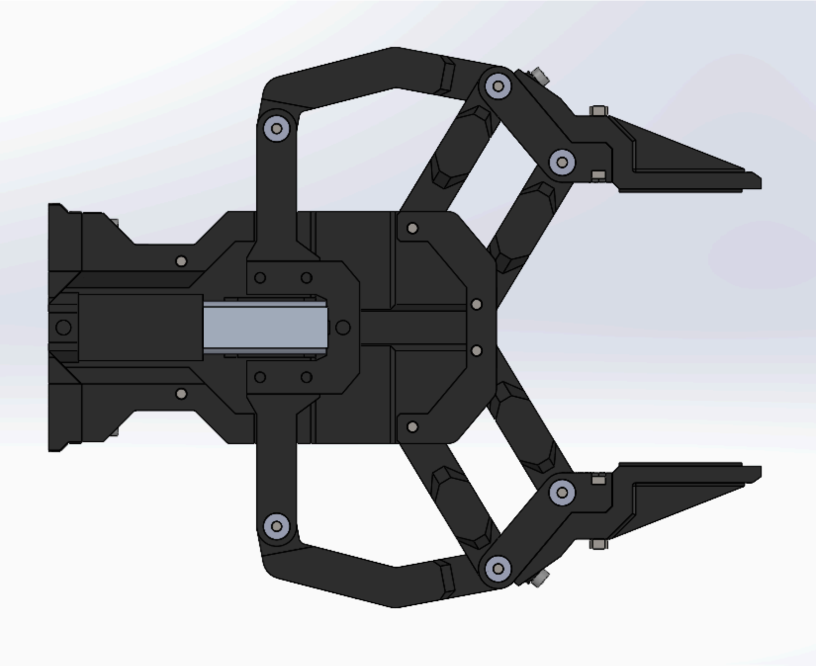

Figure 11 - Gripper assembly cross-section

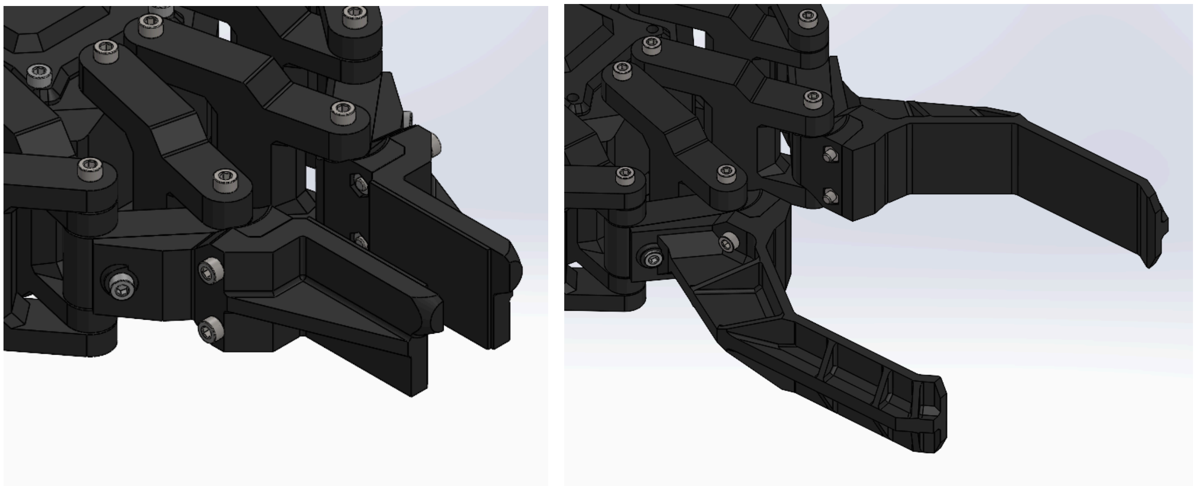

Figure 12 - Gripper fingertips

CIRC 2023 Performance

Compared to the other rovers, our robotic arm performed well in

- **Stability**: We had deflection and position instability due to the harmonic gearboxes.
- **Aesthetic**: Our robotic arm had a much more professional look than most robotic arms
- **Torque**: There was enough available torque to lift the front end of the rover by driving the gripper into the ground.

Our robotic arm lacked in the following areas:

- **Inverse Kinematics**: Controlling the arm was done by moving each joint individually (open-loop). With inverse kinematic control, we would be able to move the arm much more intuitively.
- **Limited camera visibility**: The operator could not see well with the cameras which made it very difficult to operate the arm
- **Fingertips**: The fingers designed to hold pipes were too large for the pipes in the water redirection task and the soil claws were not able to scoop soil effectively. Additionally, the fingers were not wide enough to press both buttons on the panel at the same time during the arm dexterity task.

References

[1] Inertia Ratio Introduction: 7 Resources For Understanding Inertia & Inertia Mismatch | automate.org.

[2] Inertia Ratio: Understanding Inertia Ratio and Its Effect On Machine Performance