Robotic Arm Design

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Version 1

Purpose

The purpose of this report is to document the various design decisions for the robotic arm to be used in the 2024 CIRC. The robotic arm is the rover's primary method of manipulating the environment around it. For CIRC 2024, the tasks that require the use of the arm include Precision Infrastructure and Payload Extraction, Arm Dexterity, and Search and Recovery. The robotic arm was designed to be dextrous, light, and robust.

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.

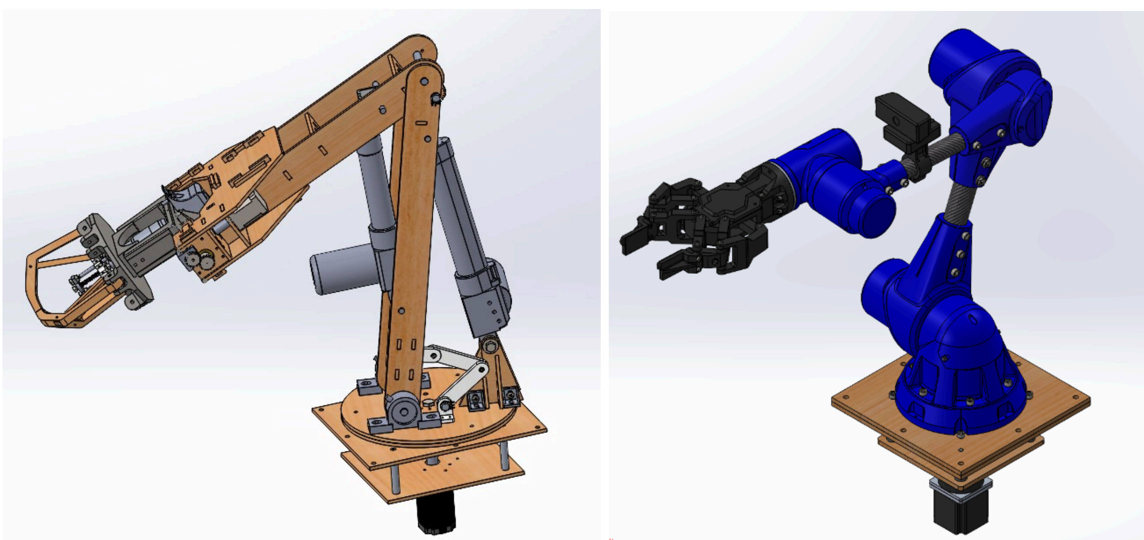
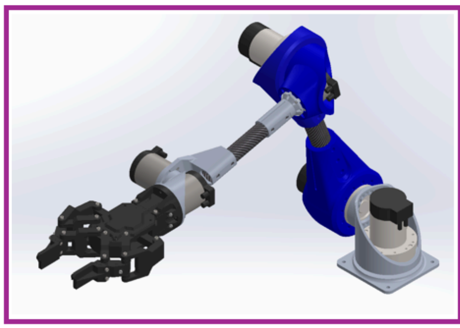


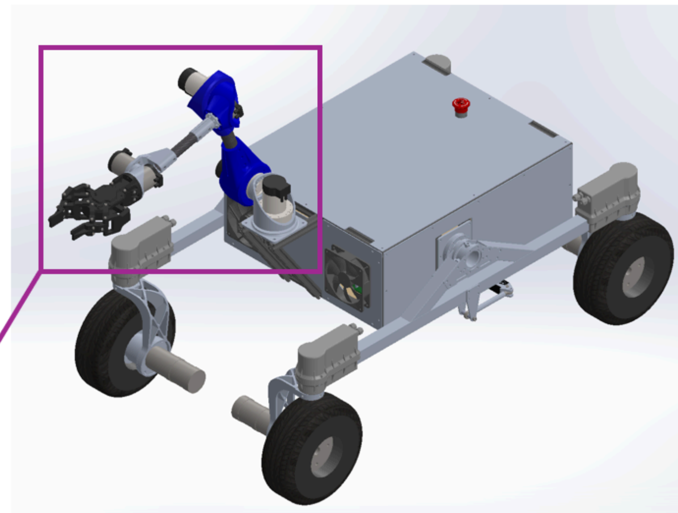
Figure 1: Wooden prototype arm (left) vs. CIRC 2023 arm (right)

Design Specifications

This year's arm was a significant upgrade to last year's. We added an additional degree of freedom (6 DOF), reduced it's mass by 1.5kg while maintaining stiffness, and standardized the communication protocol for each actuator to CANopen.

Parameter	Value
Degrees of Freedom	6
Payload	5kg
Reach	860mm
Cost	$3000
Mass	6.0kg





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Kinematics Design

6 DOFs were chosen to provide enough dexterity for the complicated tasks such as turning knobs, and plugging in USB ports. An 860mm reach was selected as the minimum length required to grab objects from the ground.

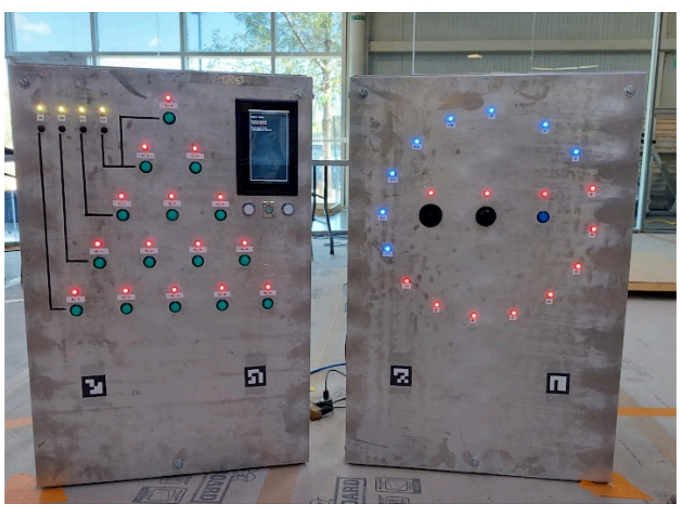


Figure 2: Arm Dexterity Task – Control Panel

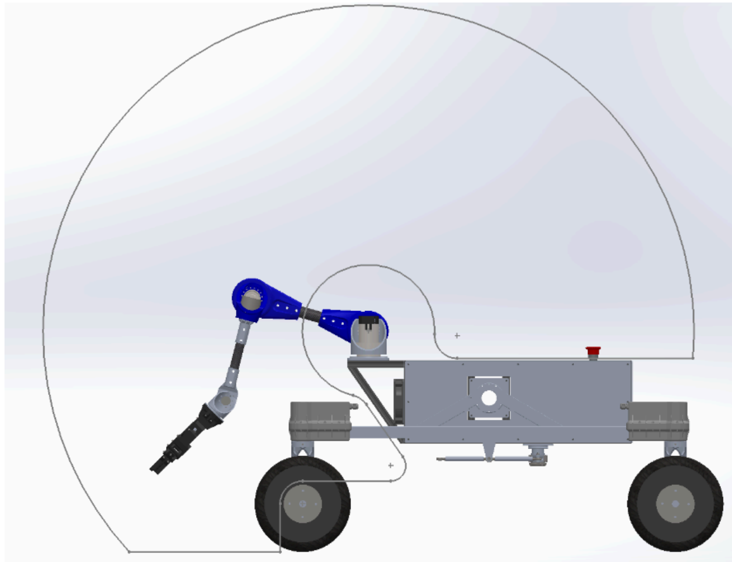


Figure 3: Robotic Arm Workspace

The arm link lengths are based on human length ratios. This is a reasonable basis as human arms are optimized for dexterity. The designer can also tune these length ratios to optimize for manipulability as discussed in the Manipulability Measures section.

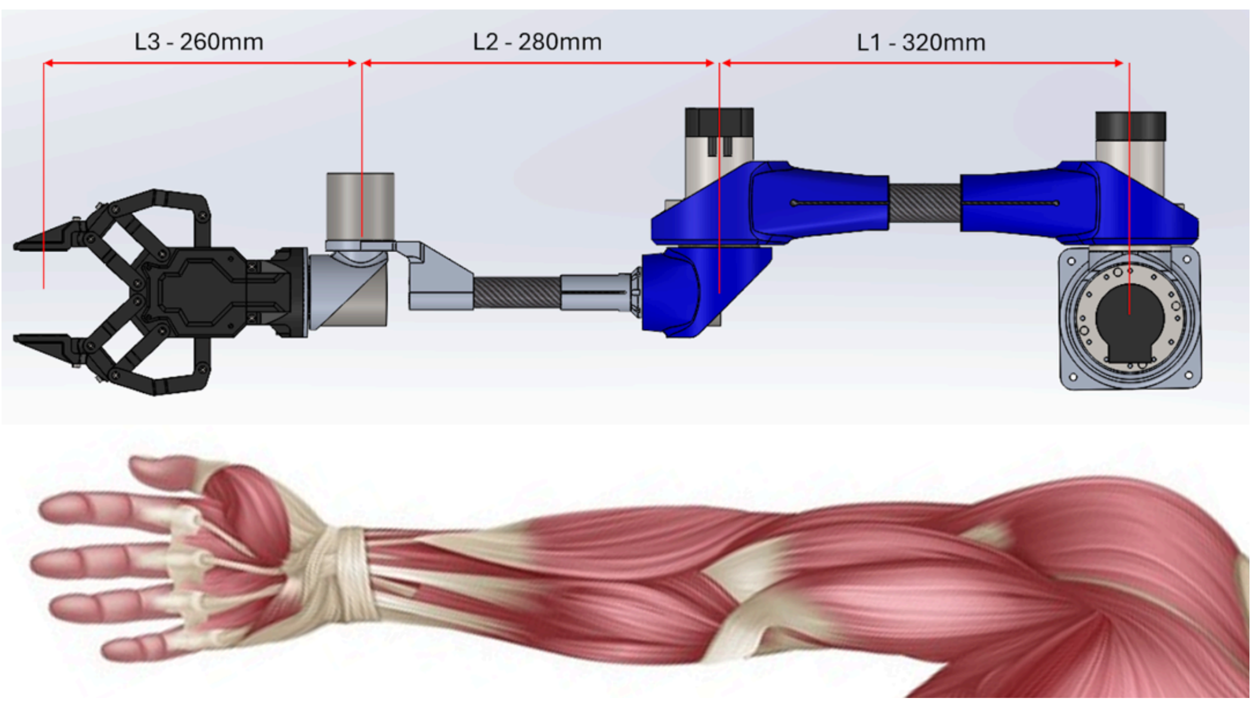


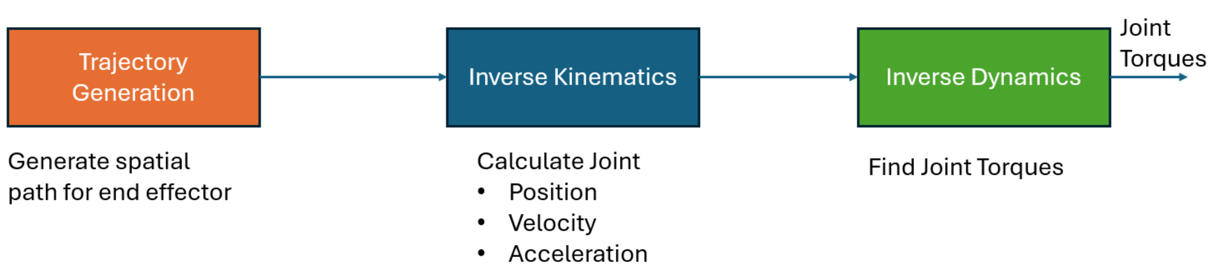
Figure 4: Robotic Arm compared to human arm length ratios

Spherical Wrist

The main reason for selecting a spherical wrist was to simplify the inverse kinematics. With spherical wrists, you can decouple the wrist translation from rotation since all wrist axes intersect at a common point. This allows the analytical solution of inverse kinematics to be easily solvable. However, it may be worth investigating the design of a non-spherical wrist, as seen on the UR robots for higher dexterity.

Dynamic Analysis

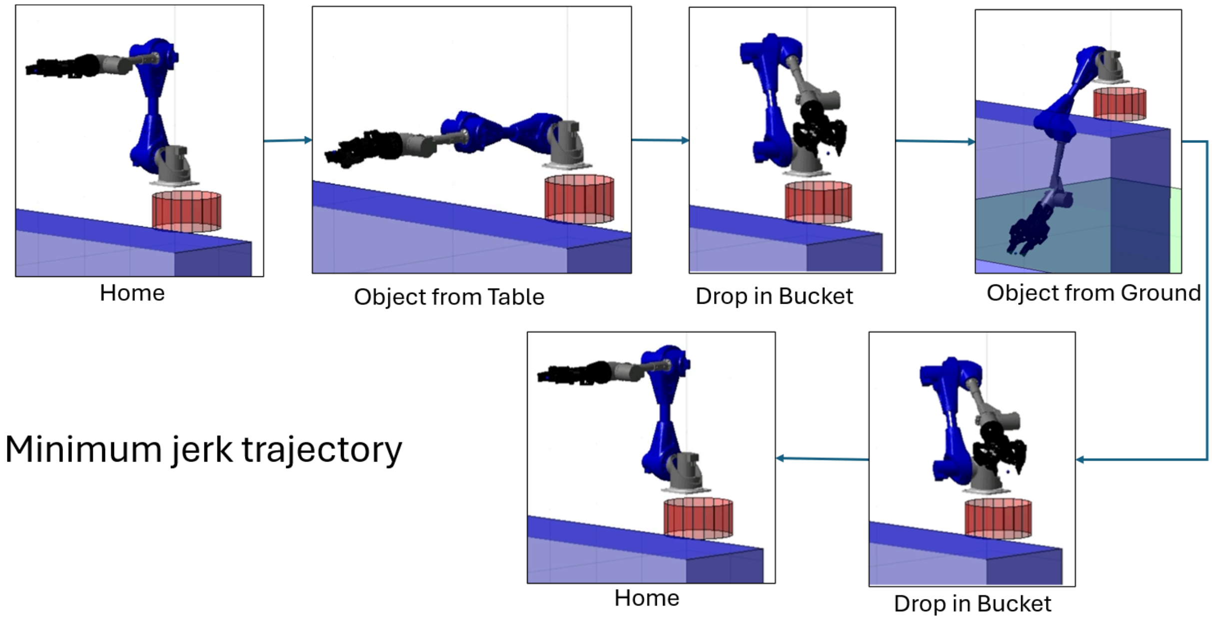
To size the actuators, we first need to determine the joint torques and speeds for each joint. The MATLAB Robotics System tool was used since it offers easy access to functions for forward and inverse kinematics, inverse dynamics, and visualization.



Trajectory Generation

First, a trajectory is generated using several waypoints that are representative of a realistic duty cycle during competition. In reality, these waypoints are arbitrary and can be selected according to the arm's designer. The time for the motion was 10 seconds, which is also arbitrary. The waypoints are stitched together using a minimum jerk trajectory optimizer. The waypoints are described below:

1. Start in the home position
2. Extend the arm fully to grab an object from the table
3. Drop the object in a bucket
4. Pick up an object from the ground
5. Drop the object in the bucket
6. Return to the home position



You can view the animation of this here: Robotic Arm Trajectory.mp4

Using the MATLAB Script

1. You can download the files MATLAB files here: MATLAB Files
2. You'll need to install the Robotics System Toolbox and download the URDF folder to run the script: ASY, ROBOTIC ARM 2024, URDF
3. Change the file path of the URDF:

```
% Load your own robot model from URDF. Change filepath accordingly
robot = importrobot("C:\Users\corne\Documents\URDF EXPORT, ROBOTIC ARM 2024\ASY, ROBOTIC ARM 2024, URDF\urdf\ASY, ROBOTIC ARM 2024, URDF.urdf");
```

4. If you have your own robot you would like to import, you'll need to define your own URDF. This can be done using a SolidWorks URDF exporter plug-in. SolidWorks to URDF Exporter . You'll need to change the number of joints if you have an arm with a different number degrees of freedom.

```
numJoints = 6; % Number of joints
```

Inverse Kinematics

With the motion profile from trajectory generation, we can now find the joint-space positions, velocities, and accelerations for each joint.

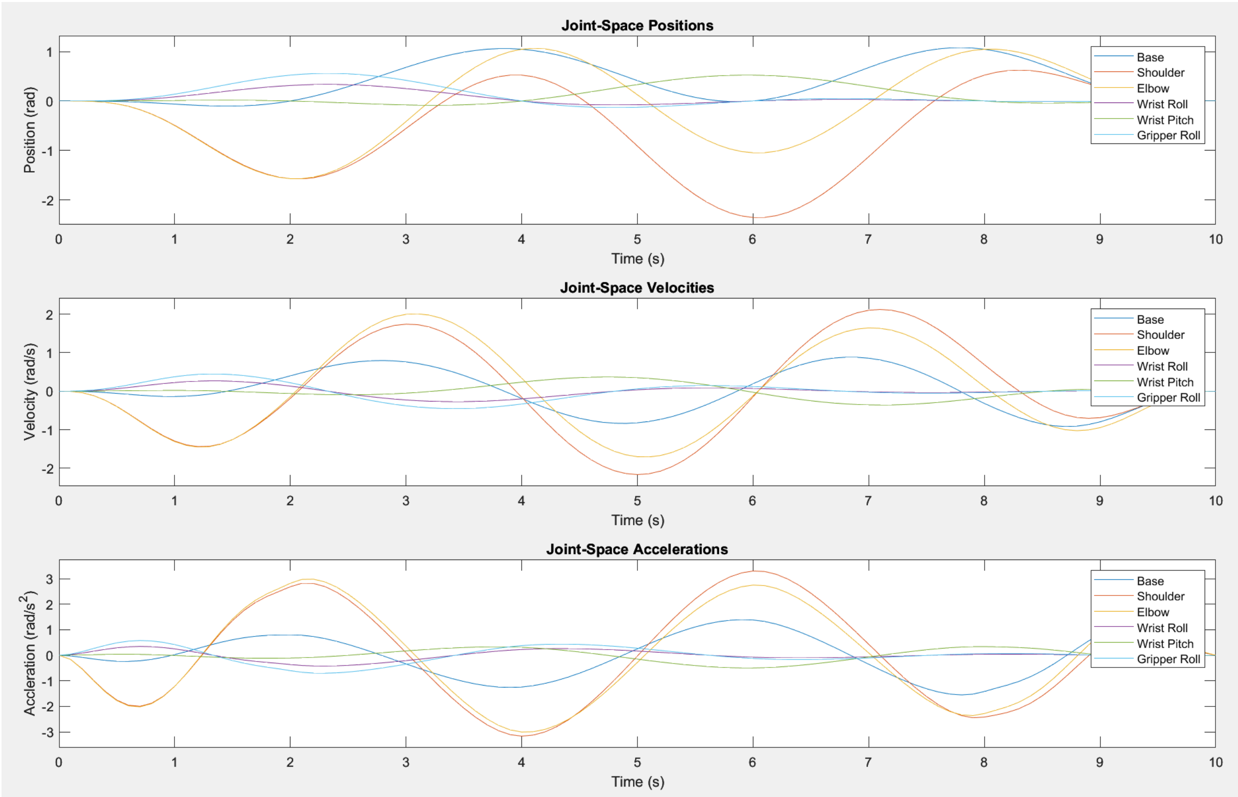
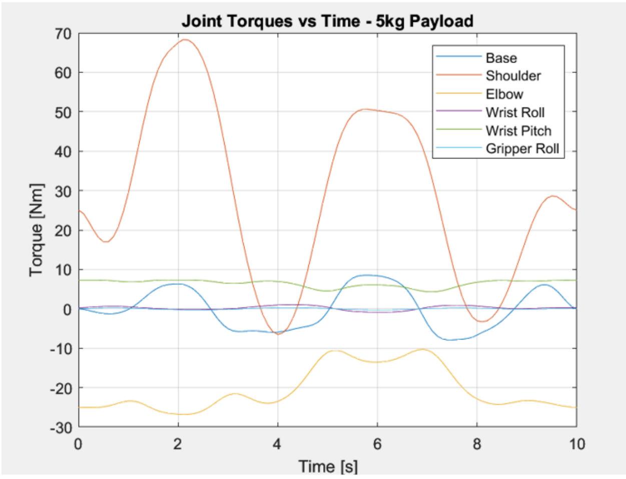


Figure 5: Joint Space Position, Velocity, and Acceleration

Inverse Dynamics

The inverse dynamics algorithm takes the joint-space positions, velocities, and accelerations and outputs the joint torques necessary for the required motion. We can now easily extract the RMS torque and peak torque for the joints.

$$Joint\_Torque = Inverse\_Dynamics(q, \dot{q}, \ddot{q})$$

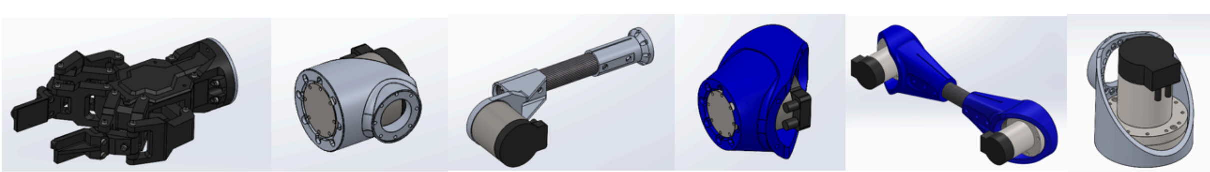


Joint	Required RMS Torque (Nm)	Required Peak Torque (Nm)
Base	5.08	8.54
Shoulder	36.05	68.28
Elbow	21.19	26.83
Wrist Roll	0.55	1.05
Wrist Pitch	6.49	7.32
Gripper Roll	0.17	0.31

Figure 6: Joint Torques with 5kg Payload

The reflected inertia of the rotor must be added to each of the links to represent the apparent inertia of the link. Since the gear ratios in robotics are high and reflected inertia scales with the gear ratio squared, the reflected inertia often dominates the dynamics. Note that adding the reflected inertia directly to the link will provide an overestimate for joint torques as each joint 'feels' the reflected inertia of its own rotor, not the others.

$$\underbrace{\boxed{I_a}}_{\text{Apparent Link Inertia}} = \underbrace{\boxed{G^2 I_R}}_{\text{Reflected Rotor Inertia}} + \underbrace{\boxed{I_L}}_{\text{Link Inertia}}$$



Add reflected rotor inertia of i-1 link to URDF inertia matrix

Actuator Selection

For controllability, minimizing backlash is highly important. Typically there are three options for low backlash drives in robotics, each with its own pros and cons:

1. Harmonic Gearboxes
2. Cycloidal Gearboxes

3. Precision Planetary Gearboxes

Harmonic drives are an extremely popular option in robotics for their zero backlash, low part count, and high gear ratio. However, purchasing harmonic gears in America will cost thousands, therefore, the only option is to buy them from China. We use actuators that are made by Zhengzhou Defy Reducers. To size an actuator for robotics, 3 considerations need to be made with respect to

1. Torque
2. Speed
3. Rotor Inertia

3x M4210 actuators are used at the wrist, and **3x** M4230s are used at the shoulder, elbow, and base as seen in Figure below.

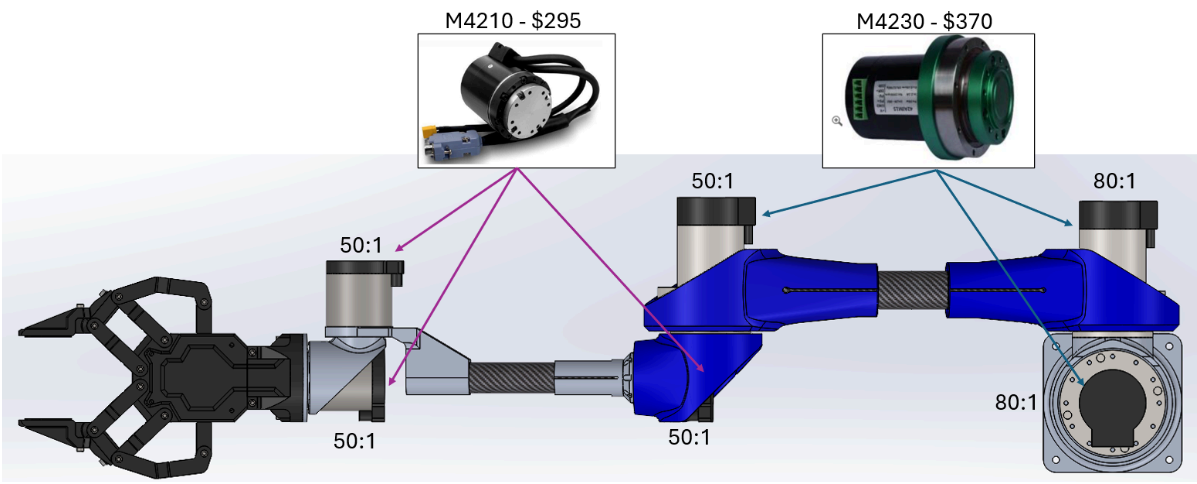


Figure 7: Actuator Layout

Joint Torque

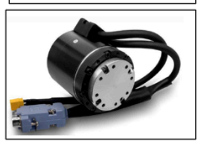
The actuator's rated torque should be higher than the required RMS torque, and the actuator peak torque should be higher than the required peak torque. We can see for a 5kg payload, the wrist pitch actuator is overloaded with respect to its rated torque. This is acceptable as long as there is sufficient time between duty cycles to let the actuator cool.

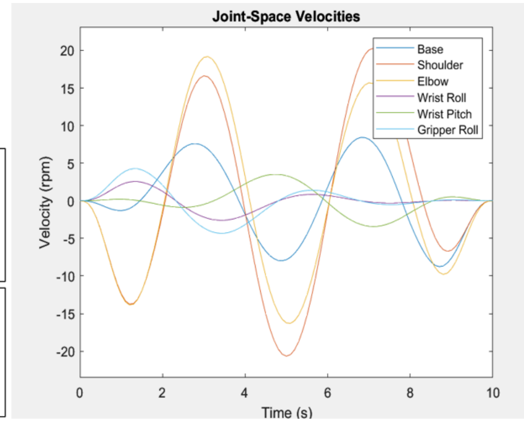
Joint	Required RMS Torque (Nm)	Required Peak Torque (Nm)	Actuator Rated Torque (Nm)	Actuator Peak Torque (Nm)
Base	5.08	8.54	51	143
Shoulder	36.05	68.28	51	143
Elbow	21.19	26.83	34	91
Wrist Roll	0.55	1.05	3.2	8
Wrist Pitch	6.49	7.32	3.2	8
Gripper Roll	0.17	0.31	3.2	8

Joint Speed

The actuator speed must be able to achieve the peak speeds required by the motion.

Joint	Required Peak Speed (rpm)	Actuator Speed (rpm)
Base	8.76	18
Shoulder	20.66	18
Elbow	19.18	18
Wrist Roll	2.59	40
Wrist Pitch	3.51	40
Gripper Roll	4.32	40



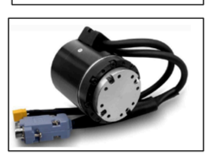


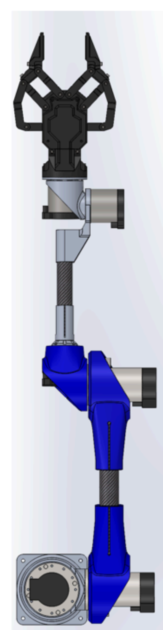
Rotor Inertia

Typically, in servo applications, we need to match the load inertia to the reflected rotor inertia for controllability and energy efficiency. Note that this is a rule of thumb because it does not account for drive stiffness or friction (controllability is influenced by stiffness, friction, and inertia). For simplicity, we can find the maximum load inertia by looking at the full extension pose and assuming point masses at the joints, with 5kg at the gripper.

- Inertia ratio should be $\frac{I_L}{I_R} \approx 1$

Joint	Reflected Rotor Inertia (kgm^2)	Maximum Load Inertia (kgm^2)	Inertia Ratio
Base	4.416	2.268	*1.00*
Shoulder	4.416	2.257	*1.00*
Elbow	1.725	1.369	*0.79*
Wrist Roll	0.228	0.0235	*0.23*
Wrist Pitch	0.228	0.203	*2.15*
Gripper Roll	0.228	0.0209	*0.22*





We can see that the inertia ratio for wrist pitch is 2.15. This is acceptable since the application does not require a high amount of precision and dynamic performance. Another thing to note is that Elbow, Wrist Roll, and Gripper Roll have inertia ratios less than 1. This is indicative of an over-spec'd actuator or the motion profile needs to be revised.

You can read more about inertia ratios here:

- Inertia_Ratio_on_Controllability.pdf
- Energy_Management_Inertia_Ratio_Servomotor_11_2_15_FINAL.pdf

Mechanical Design

In most robotics applications, we need to maximize the stiffness-mass ratio of the robot. The links are carbon fibre tubes joined by aluminum parts to mount the actuators. All the parts are CNC machined except for the blue parts which are printed from PETG. We got sponsored by ZTL to CNC machine our aluminum parts for $600. Another benefit of this design is that the tubes can be easily switched to increase the reach of the arm, at the sacrifice of maximum payload or motion speed.

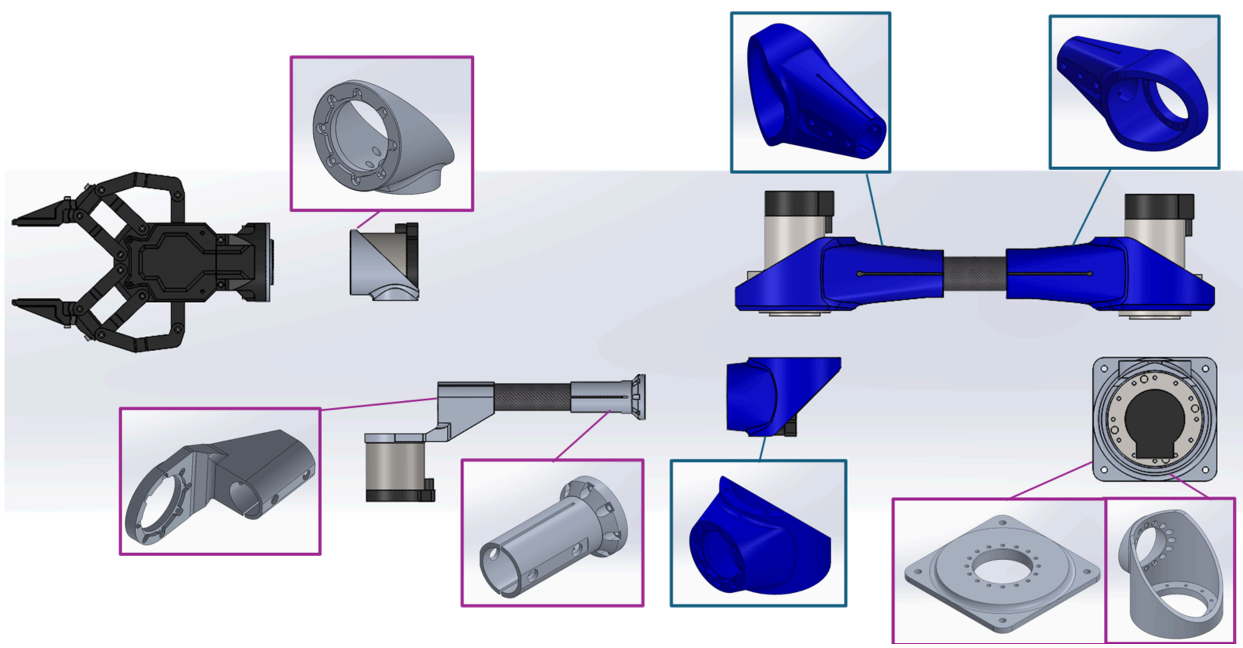


Figure 8: Arm Exploded View

Manipulability Measures

You can also adjust the manipulability measures by changing the lengths of the tubes. These measures indicate how effectively the robot can generate velocity or force in a specific direction. They are visualized using velocity and force ellipsoids, where the volume of the ellipsoid is proportional to the robot's capability to produce movement or force.

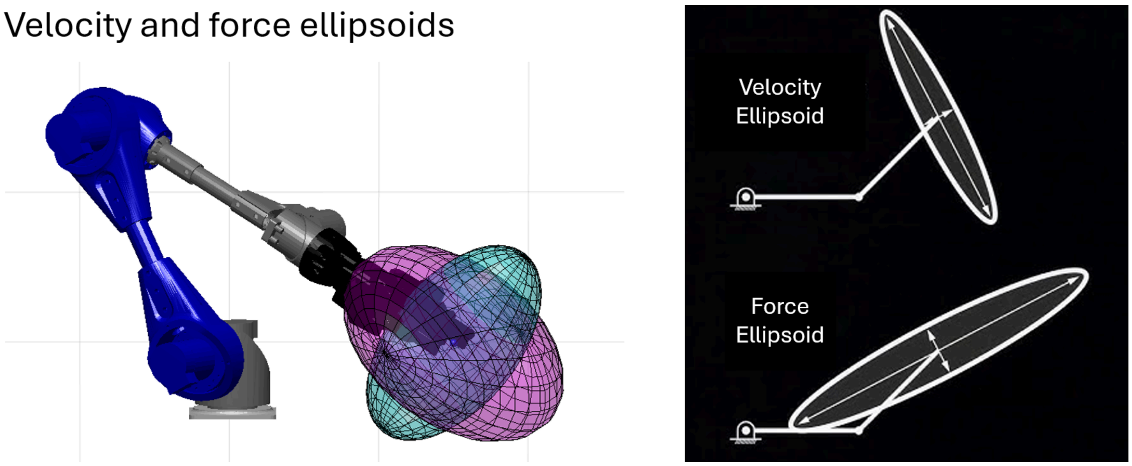


Figure 9: Velocity and Force Ellipsoids

If we plot velocity and force manipulability for a simple 3 DOF RRR planar robot, we can see that there is an optimal band for velocity production somewhere in the middle of the workspace. The arm designer can tune where this optimal band occurs by playing with the link lengths.

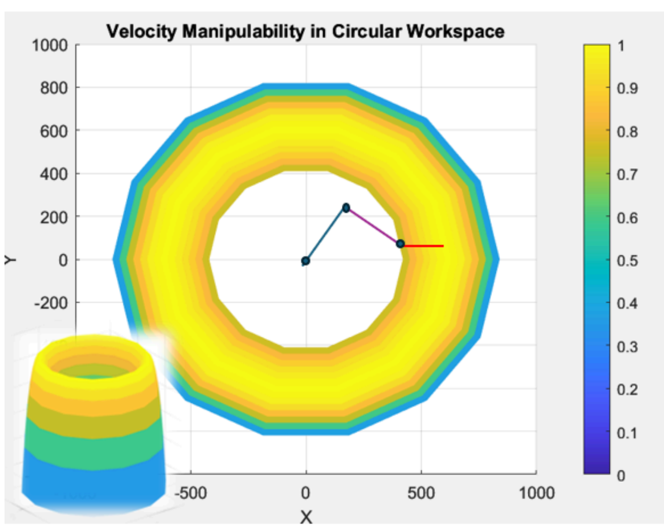


Figure 10: Optimal Band for Velocity Ellipsoid

You can read more about manipulability measures here: [5.4. Manipulability – Modern Robotics]()

Bill of Materials

The cost and mass of the components is shown in the table below.

Table 1 - Cost and Mass Breakdown

	Cost	Mass (kg)
Actuators	$2150	4.17
Machined Parts	$600	0.72
3D Printed Parts	$60	0.65
Carbon Fiber Tube	$100	0.07
Gripper	$120	0.36
Total	**$3030**	**5.97**

Assembly

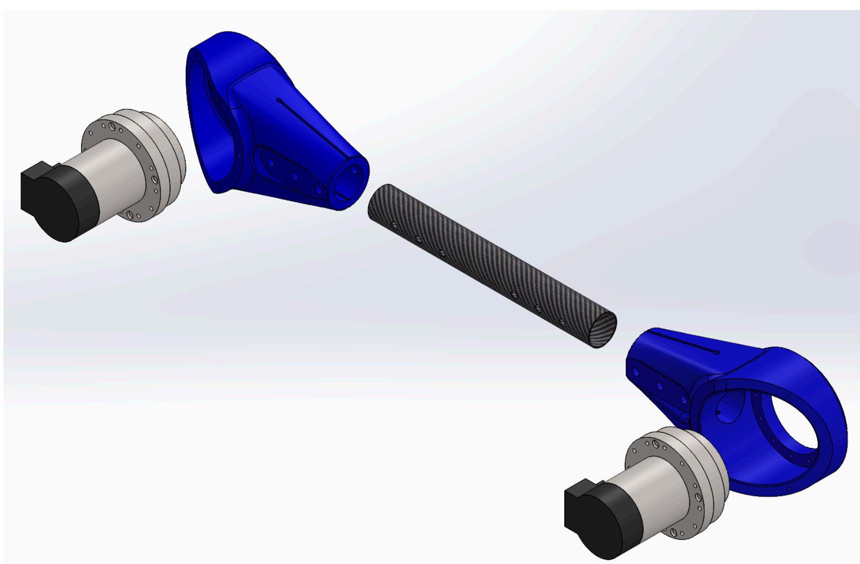


Figure 11: Upper Arm Link

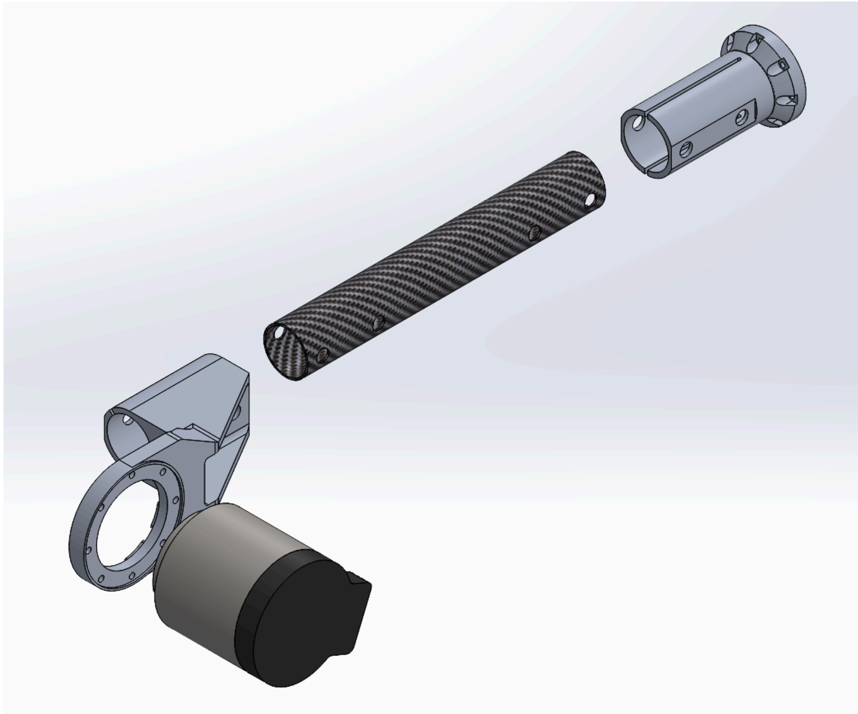


Figure 12: Forearm Link

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). The linkage parameters were tuned to flatten out the mechanical advantage curve over a wide range of actuator strokes.

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

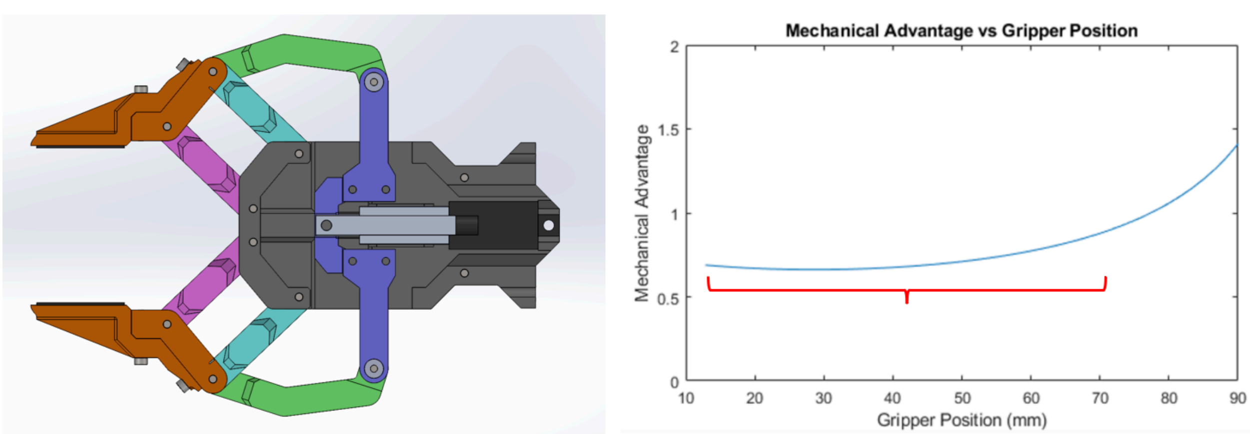


Figure 13 - Gripper cross-section

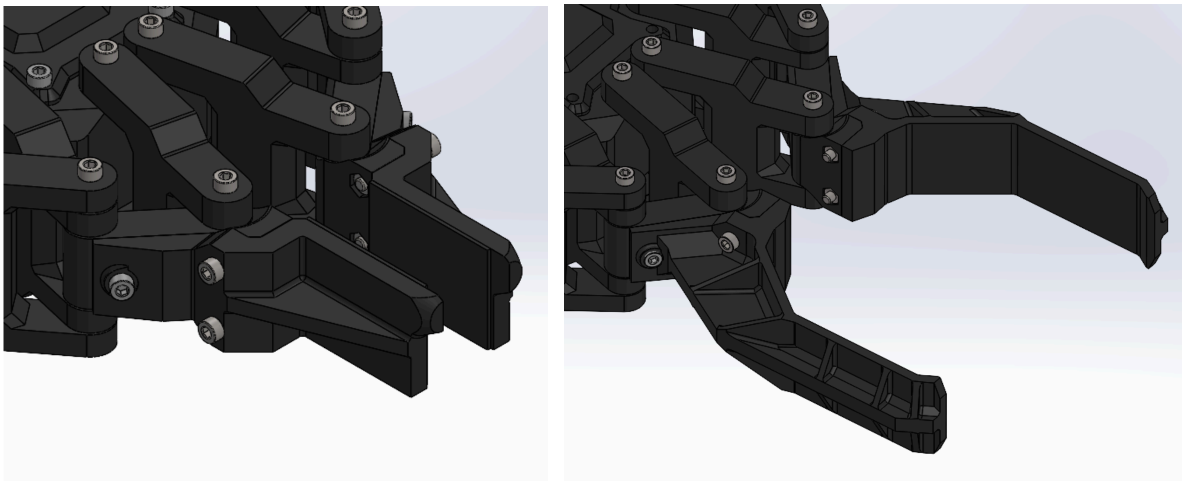


Figure 14 - Gripper fingertips

New Aluminum Parts

Converting the PETG parts to aluminum will increase stiffness significantly and remove the low-frequency modes caused by joint compliance at the shoulder.

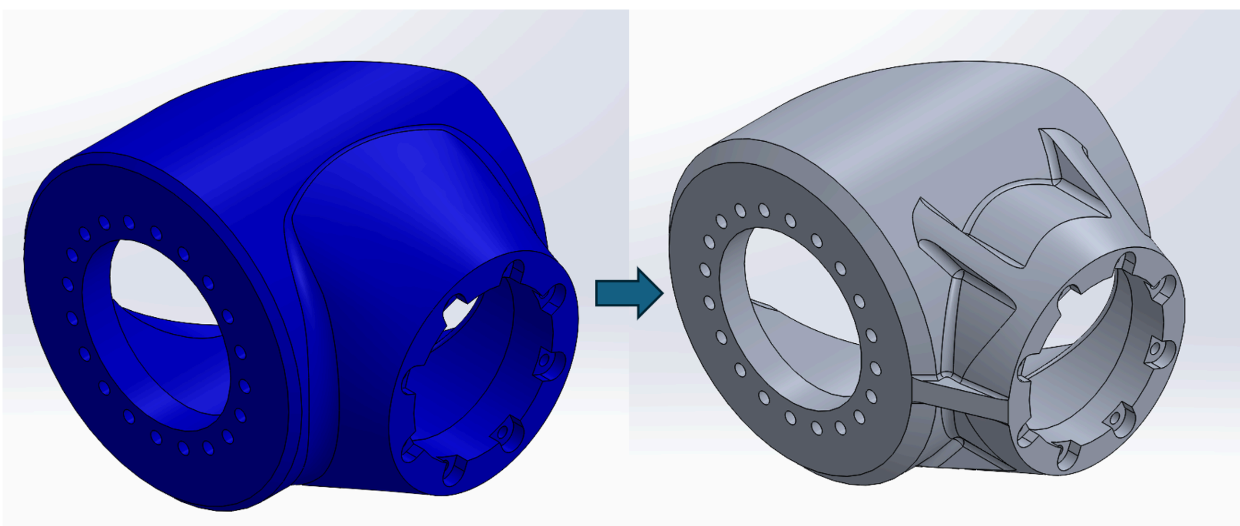


Figure 15: Elbow Link