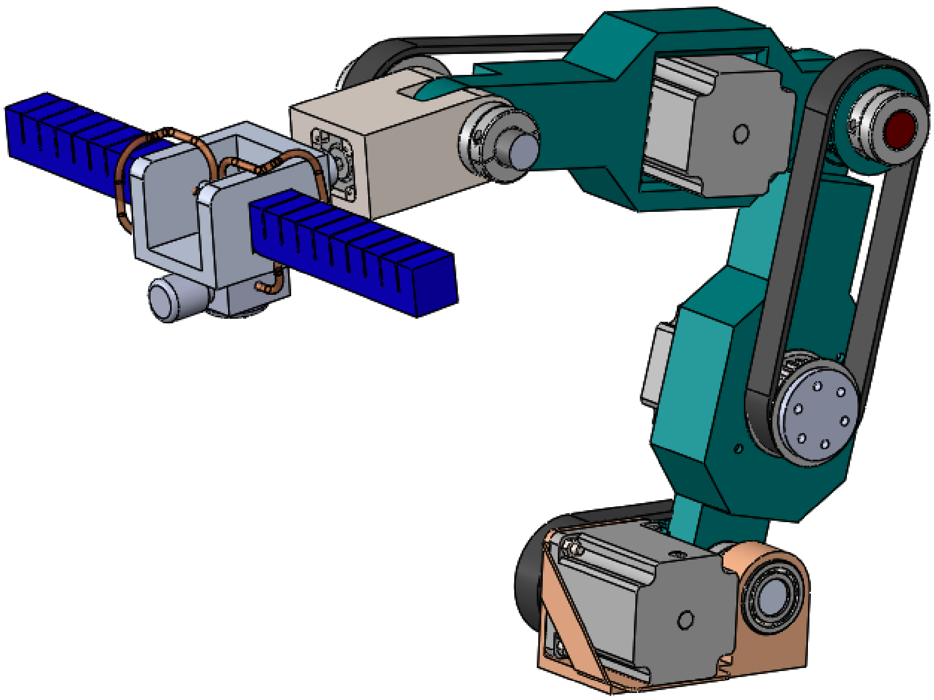


Mars Rover’s Robotic Arm

Michael DeCapua
Alex Klausenstock
Subhraneel Sarkar
Monique Reid

MCEN 5045: Design for Manufacturing
Professor Dan Riffell

April 19th, 2022

Table of Contents

Table of Figures

Table of Tables

Executive Summary

A light-weight strong four axis robotic manipulator for use on other celestial bodies was re-designed for mass manufacturability (approximately 100,000 units). The estimated unit price decreased by 28% or $216.75 due to subassembly design changes. The practical assembly efficiency was increased by 16%. To achieve this water jet cutting metal plate was replaced with investment casting. A high volume, high capital cost process was used to manufacture complex components for a lower part count easier to assemble lower cost Aluminum arm. Self-locating features for easy assembly are now present throughout these redesigned cast parts. Features and sites for component mounting which were previously absent were also added. The number of purchased components was decreased by integrating parts into existing custom components. Parts that otherwise would have had to be purchased at an inflated price and assembled. Notably two custom FDM 3D printed pneumatically actuated flexible Thermoplastic Polyurethane (TPU) gripper components replaced an 11-component conventional mechanical gripper assembly. Finite element analysis and simulation was done in ABAQUS 2021 and a test plan for gripper actuation was made to see the accuracy and precision of bending. The concepting and redesigning of this assembly have been noted in this report.

Introduction

Space robotics has been an up-and-coming field for the last few decades between the interest in space exploration and satellite data collection. Being that large corporations such as SpaceX and numerous start jobs have spoken on the potential of travel to Mars, there has been a potential market to open for having autonomous equipment on other planets. This project has been inspired by the Mars Rover Challenge, which is a yearly competition between universities for data collection and sample retrieval in the deserted area of Utah, USA. Out of the 99 teams that have applied to compete in the 2022 University Rover Challenge, only 36 teams have been accepted to travel out to Utah, USA to compete.

Our team is developing this manufacturing report to understand the fabrication complexities that will be included in developing a robotic arm for CU Rover's robotic assembly. The development of this report will allow the CU Rover team to understand the cost and measure of the manufacturing decisions that will be included for fabrication with hopes to compete in June of 2023. For course purposes, our team's economic analysis will make economic decisions that will test a market of sale for 100,000 assemblies sold nationwide. This assembly represents a practical robotic arm that our team could see for applications in hazardous environments for emergency responders and household uses for disabled communities. In refining this design, our group has taken a material analysis and DFA approach to studying this assembly.

Product Description

Currently, there are other universities working toward developing Mars Rovers for this university competition. This year the University of Colorado Rover team is new to this campus and developing its first robotic arm assembly. The robotic arm shown below has four degrees of freedom at the base, elbow joint, wrist joint, and gripper to the arm. Most robotic arms in this competition have one gripper to complete the tasks that will be done on a spacecraft mission. Our team has developed a soft robotic gripper that is a modular subassembly to the rest of the arm. The ideation is that multiple gripper configurations could be used on this robotic arm for completing various tasks. The soft robotic actuator has been selected as the primary gripper in this report in an enthusiastic approach of having an original and novel design to the competition since soft robotics is a new and upcoming research study at CU Boulder.

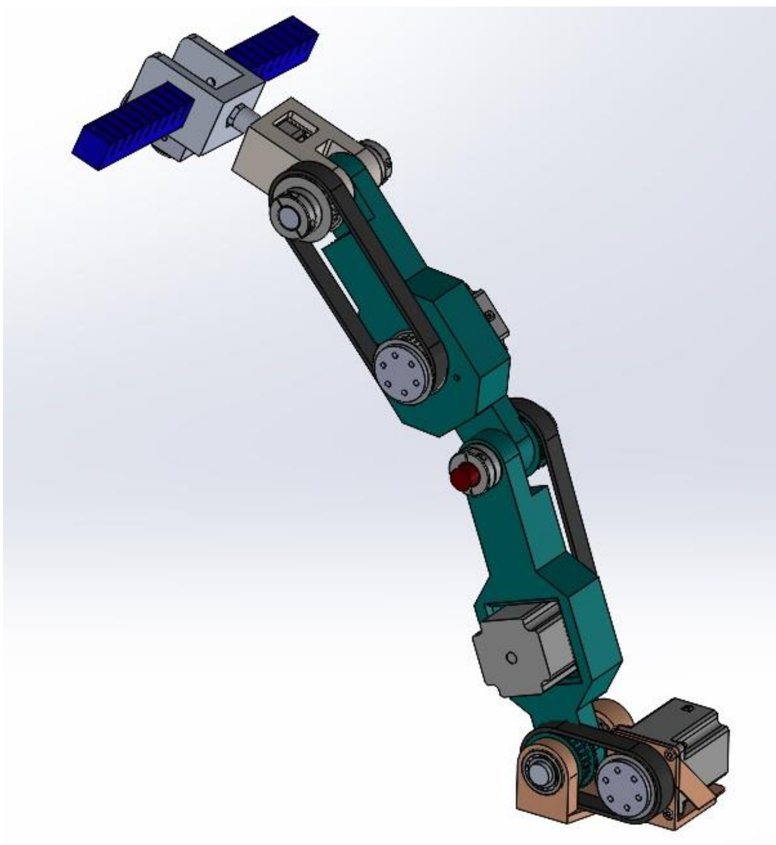


Figure 1: Redesigned Robotic Arm Assembly

Black Box Diagram

The black box model is a simple illustration of the fundamental signals of energy, commands, and material input and output for the device of interest, a soft gripper robotic arm. This insight helps our team understand the fundamentals of our device and gain perspective on overall functionality.

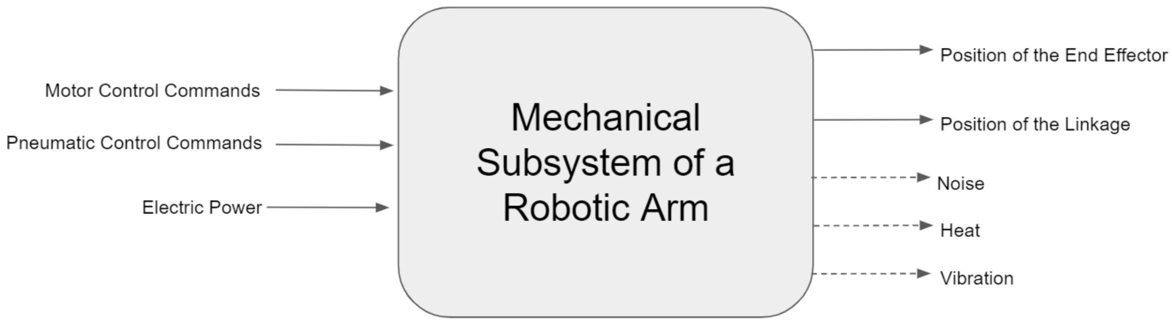


Figure 2: Black Box Diagram of the Mechanical Pneumatic Robotic Arm

Glass Box Diagram

Displayed below is a glass box diagram that describes the physical acts of nature that occur between the mechanical system and the pneumatic system. The mechanical system receives motor controls and power to command the stepper motors to maneuver the robot. This results in displacement in the position of the linkage. The pneumatic system receives pneumatic commands from the regulator and actuator. This is what actuates the soft gripper fingers to grab and move components around the robot.

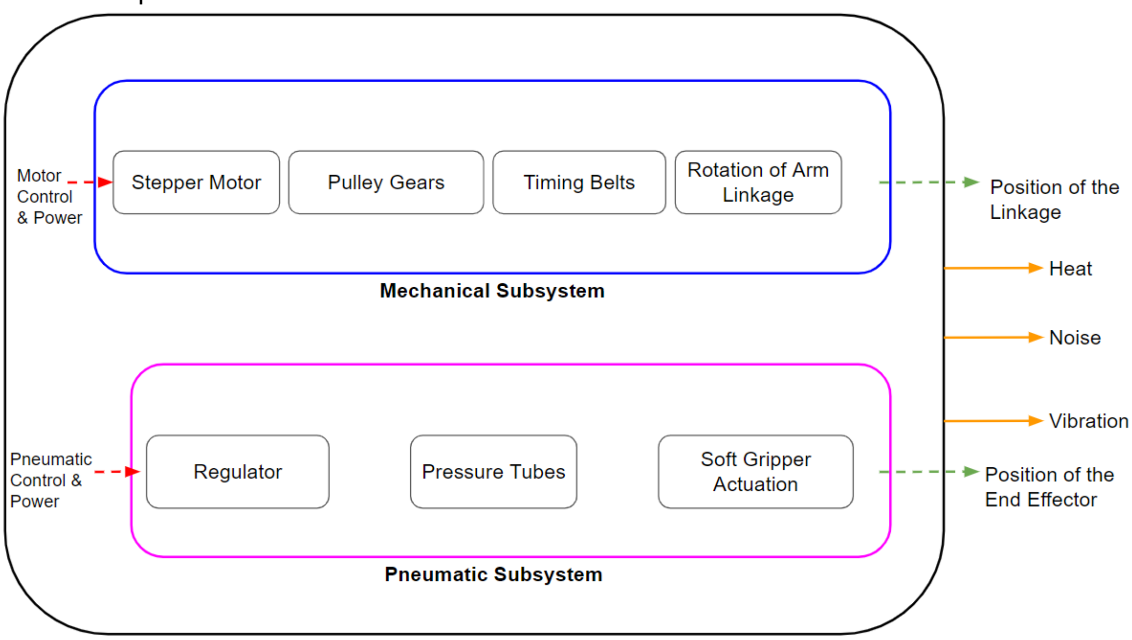


Figure 3: Glass Box Diagram of the Robotic Arm Mechanical and Pneumatic Assemblies

Gantt Chart

To schedule and be mindful of our design time, our group developed a Gantt chart to list out tasking throughout the semester. This chart can view here:

TASK NAME	START DATE	TOTAL DAYS FROM START	END DATE	DURATION* (WORK DAYS)	DAYS COMPLETE*	DAYS REMAINING*	PERCENT COMPLETE
DFM of Mars Rover Arm							
Concept Idea for a DFM Project	3/15	0	3/16	2	2	0	100%
Research Standard Parts	3/17	2	3/18	2	2	0	100%
Categorize the assembly into sub assemblies	3/18	3	3/19	2	2	0	100%
Inspect Part Number and Interfaces	3/20	5	4/12	24	24	0	100%
Model Redesigned Assembly	3/21	6	4/13	24	24	0	100%
Develop Engineering Drawings for each part	4/7	23	4/14	8	8	0	100%
Go through DFA Analysis	4/12	28	4/19	8	8	0	100%
Manufacturing and Material Analysis	4/12	28	4/19	8	8	0	100%
Develop Patent Search	4/18	34	4/19	2	2	0	100%
Economic Analysis of Products	4/18	34	4/19	2	2	0	100%
Due Date of Final Report	4/19	35	4/19	1	0	1	

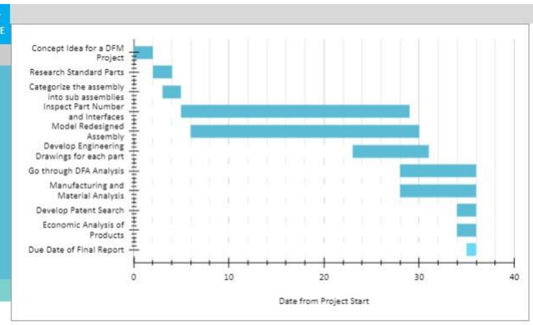


Figure 4: Spring 2022 Gantt Chart- DFM Robotic Arm

Fishbone Diagram

The fishbone diagram decomposes the Rover Robotic arm into four major subassemblies connected to the main body. The robotic arm itself is shown at the head of the fish with a horizontal line connecting the four angles' lines. Each of these angled lines represents a subassembly with shorter horizontal lines denoting individual components within that subassembly. The parts in black will be purchased off-shelf from various vendors. The parts indicated in red are custom investment-casted and the one in purple is 3D printed.

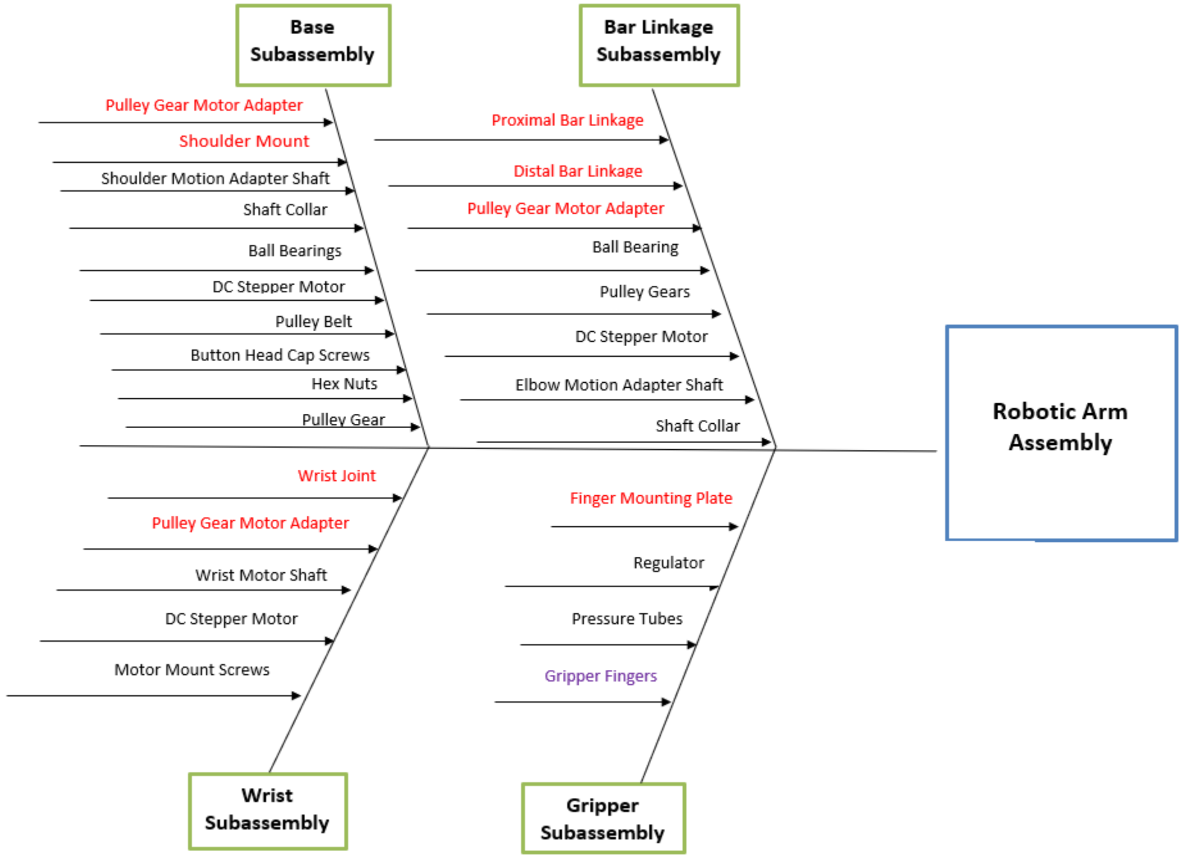


Figure 5: Fishbone Diagram of the Robotic Arm Assembly

Patent Search

While an initial design was created for the rover robotic arm, a patent search needed to be performed for the redesign. The purpose of this search was to accomplish two things. First, by looking at other ideas available in patents, it became possible to get more ideas on potential design iterations to the initial design to make it more robust, compliant, versatile and user friendly. Additionally, it was important to perform a patent search to understand what products and ideas already exist to make sure that no patent infringement occurs.

(1) The first patent we found was US 11,045,959 B2 published on Jun 29, 2021, titled, "End of Arm Tools for Soft Robotic Systems" as shown in Fig6.

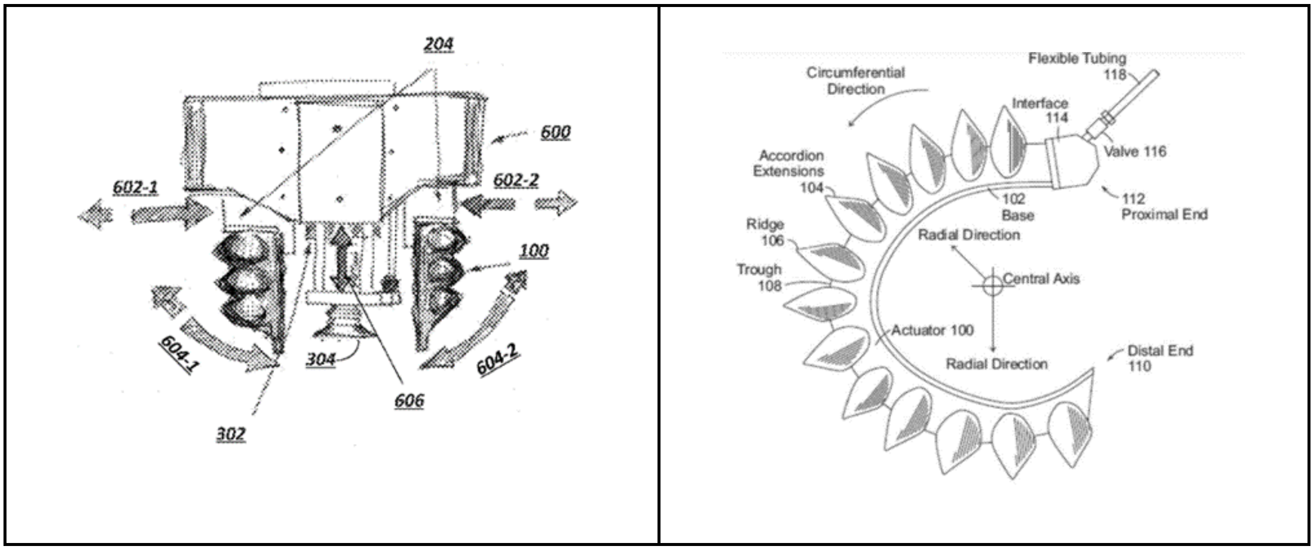


Figure 6: US 11,045,959 B2

In this patent, a soft robotic grasping system for grasping an article includes a gripper hub and a finger actuator that applies a first pressure change. A plurality of soft robotic fingers each include an elastomeric outer surface surrounding an internal void, and each is configured to curl in a first degree of freedom when the finger actuator applies the pressure change within the internal voids. The finger actuator applies the pressure change to the interior of the hub, and the pressure change is transmitted via the linkage fluid seals and fluid passage tubes to the soft robotic fingers. Additionally, the system includes a suction actuator that applies a second pressure change, and a suction cup configured to apply a suction force according to the second pressure change. This patent gave us the idea of using a soft gripper instead of stepper motors and the traditional end effectors made of Aluminum. This will reduce part count as well as overall weight and increase the efficiency of managing various payloads. The basic idea behind this is that soft pneumatic actuators include a hollow interior that can be filled with a fluid such as air, water, or saline to pressurize, inflate and/or actuate the actuator.

Upon actuation, the shape or profile of the actuator changes. In the case of an accordion-style actuator, actuation may cause the actuator to curve or straighten into a predetermined target shape. Interestingly, the actuator may be actuated using a vacuum to remove inflation fluid from the actuator and thereby change the degree to which the actuator bends, twists and/or extends. This makes the grasping more robust, inherently compliant, and inexpensive as this actuator has high behavioral diversity, large degrees of freedom, continuum topology and low weight.

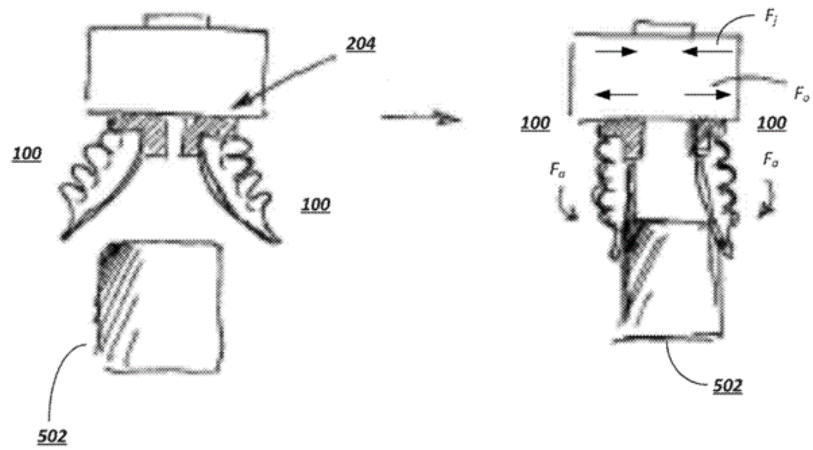


Figure 7: Pneumatic Actuation

The second patent we found was US #4,806,066 titled “Robotic Arm” which includes a robotic arm and control system comprising a multi-axis open loop system of coupled structural members, wherein each structural member is pivotally coupled to one another to form several joints, wherein position calibration is provided by way of position sensors disposed at each joint, and controls for manipulating each joint in a predetermined manner. Here, each of the structural members are controlled by one or more separate motors. The motor is coupled to the structural member by way of a cable/pulley drive train. This provides position calibration of the various structural members with respect to one another by providing drive signals to each of the motor/cable/pulley drive arrangements in response to the output states of the position sensors.

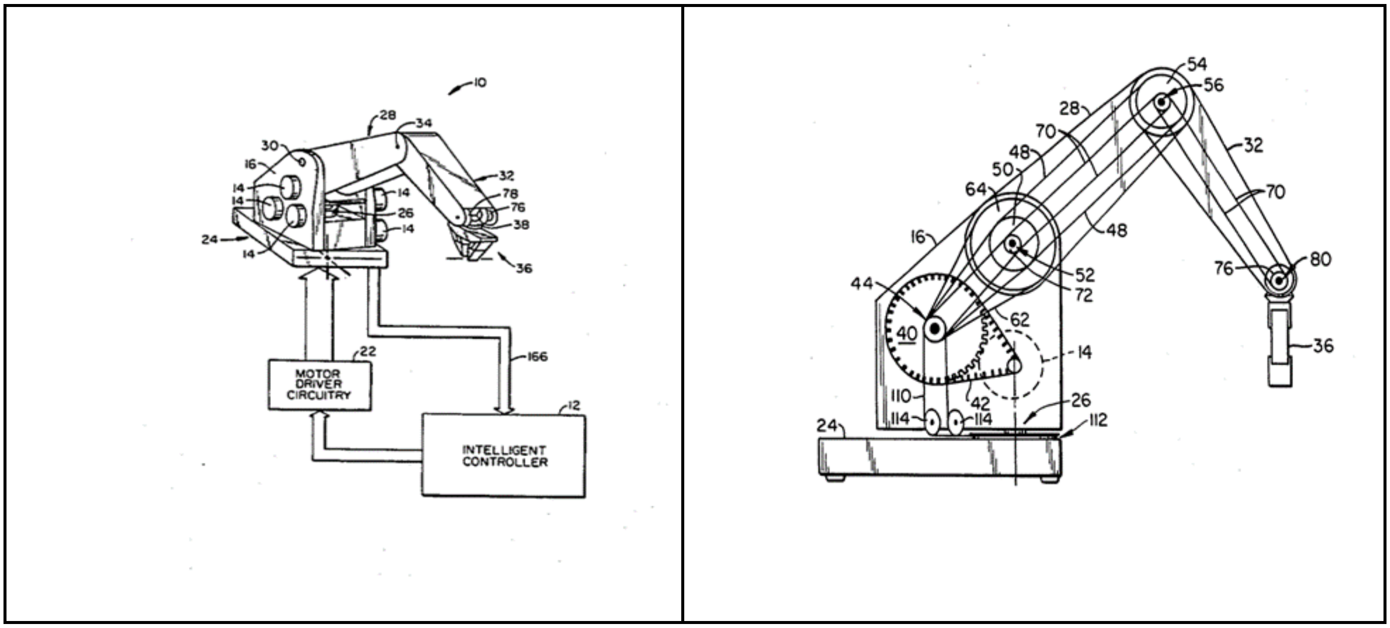


Figure 8: US #4,806,066

We have incorporated a similar motor and pulley drive system that drive all the links of the wrist, shoulder, and arm of the robot. This arrangement provides an apparatus and method for securing and routing the various drive cables to the pulley structures so that a more positive coupling between the motors and the structural members can be obtained.

Hand Sketches of Original Design and Design Changes

General Concept of Robotic Arm

The team initially started with the concept of implementing a simple, but functional, robotic arm. Below is a sketch from the ideation process which started with visualizing the pulley-belt system for the proximal bar linkage. In the beginning, our team set out to try to make the arm as symmetrical as possible, limiting the number of unique parts.

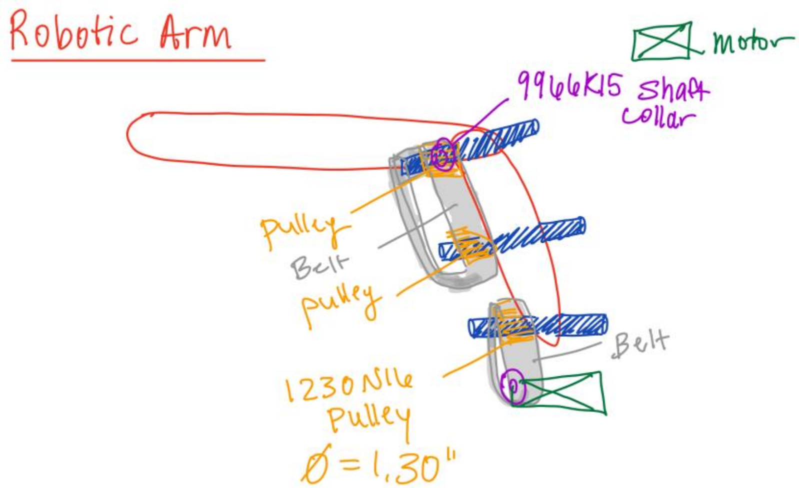


Figure 9: Robotic Arm Concept Sketch

System Redesign Sketch- Assigning Subassemblies

After conceptualizing the robotic arm, the original CAD design of the robot is presented below. The robot can be broken down into three segments: the wrist, elbow, and shoulder. The initial design had a large plate and two large pillow blocks. Initially, this base consisted of a lot of material that was not used in the most efficient way. One of the first redesign tasks was to reduce the amount of unused material and parts. The initial CAD was made of four separate linkage bars that connected the three segments together. Although this design is lightweight, the team aimed to reduce the number of parts and provide stability and support for the mechanical pulleys. The final major redesign included changing the gripper subassembly. The gripper initially presented the greatest number of unique parts throughout the entire assembly. The finger initially required three planar gears to mechanically extend and flex the fingers. Using our team's background in advanced engineering robotics, the goal was to implement a simpler mechanism for finger actuation.

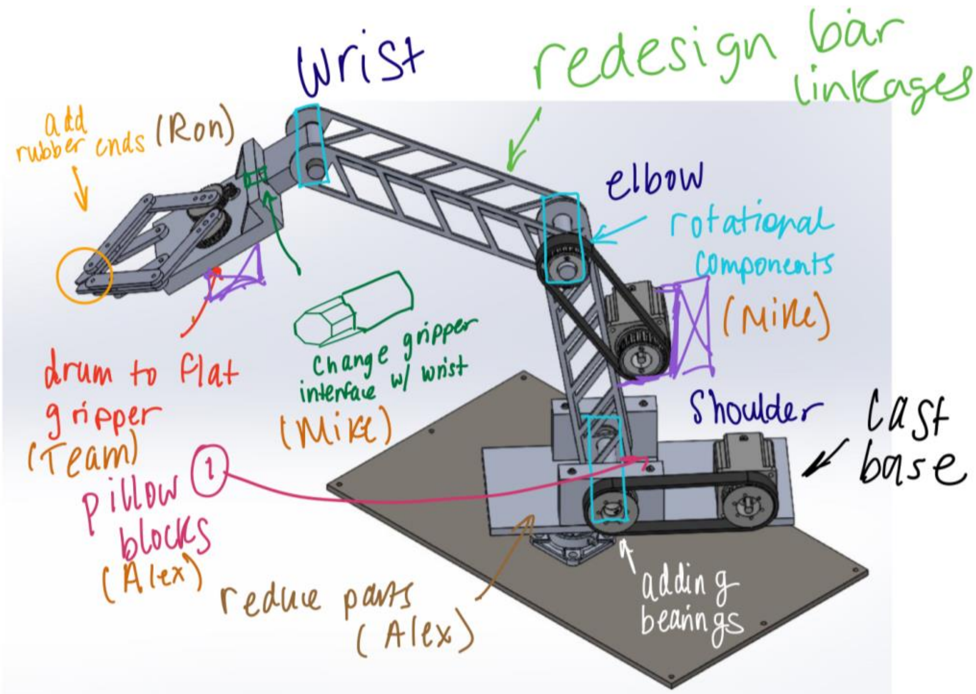


Figure 10: System Redesign Sketch- Assembly Breakdown

Base Plate Redesign Sketch

The first sketch for the base plate included creating a large bracket shape with holes for the linkage arms. The team explored a variety of material and manufacturing methods including using aluminum sheet metal or CNC machining. With each of these methods, there are limitations to how small or large the dimensions may be.

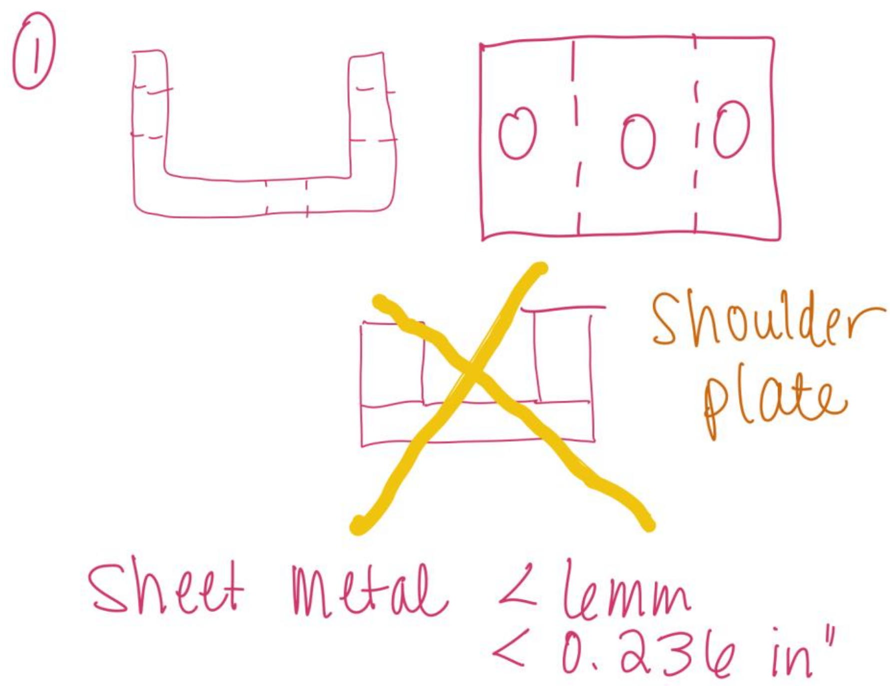


Figure 11: Base Plate Redesign Sketch

Motor Mounting Fixture Redesign Sketch

The stepper motors were initially not well constrained on the assembly. The task of the final design was to design a sturdy robotic arm that could mechanically maneuver. In the redesign, mounting fixtures or creating a clamp shape was explored for securing the motor on the shaft.

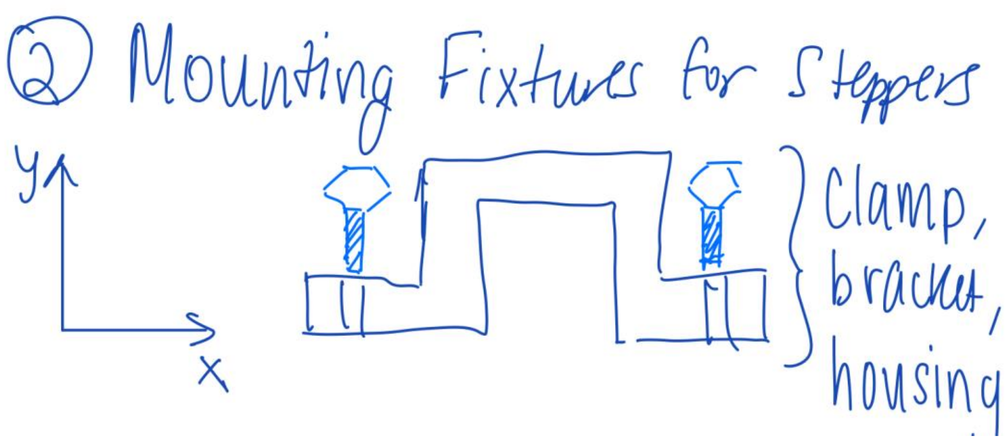


Figure 12: Motor Mounting Fixture Redesign Sketch

Bar Linkage Redesign Sketch

The bar linkage original design consisted of four identical parts. Although these parts are going to be made of lightweight aluminum, we attempted to reduce the bar linkage to two parts with additional hardware to allow the same degree of freedom. Below is a sketch of the team's design ideas before settling on the bottom right sketch that is presented in the final.

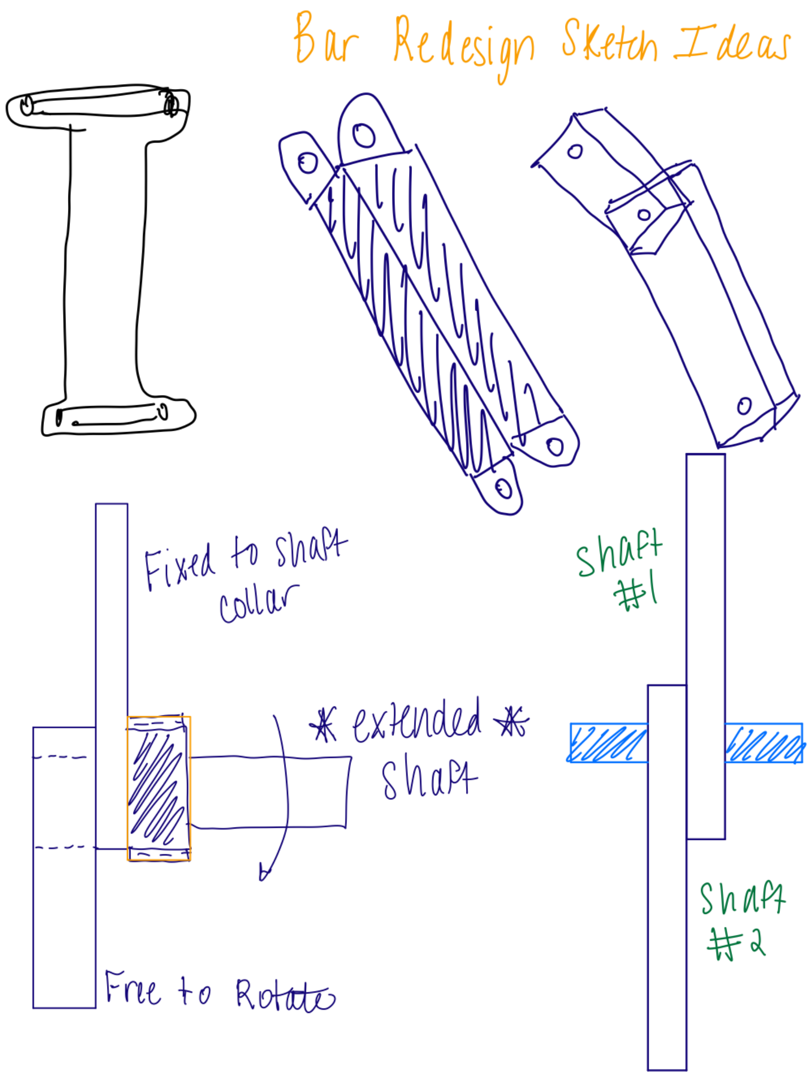


Figure 13: Bar Linkage Redesign Sketch

DFA Analysis and Comparison

DFA Overview Summary

The Design for Assembly (DFA) Analysis matrix tool was used to compare the original to the redesign of the robotic arm. This process methodically reveals opportunities to minimize the number of extraneous or unnecessary parts, standardizing when possible, and simplifying the assembly for the manufacturer. The DFA analysis proposed several problematic areas which the team focused on addressing in the revised robotic arm design. A summary table of the the key metrics and change, (**Δ**), is presented below. These metrics were then further analyzed in more detail regarding the reasoning for the change.

Table 1: DFA Analysis Summary

DFA Metrics	Original	Revised	Delta (Δ)
DFA Complexity	80.28	75.31	**-4.97**
Theoretical Efficiency (%)	29.2	39.6%	**+ 11.5%**
Practical Efficiency (%)	27.7%	43.4%	**+16.7%**
Error Proofing	0.47	0.05	**-0.42**
Handling	0.00	0.05	**+0.05**
Insertion	1.32	0.86	**-0.46**
Secondary Operations	0.63	0.38	**-0.25**

DFA Complexity

The DFA complexity provides an overall understanding of the number of parts and number of interfaces. A comparison of the original and redesign complexity analysis is presented below.

 Part Name	Number of Parts (Np)	Number of Interfaces (Ni)
Base Assembly		
Mounting plate with pillow blocks	1	7
Shaft Collar	2	2
Set Screw Shaft Collar	2	1
Bearing	2	2
DC Stepper Motor	1	2
Pully Belt	1	2
Button Head Cap Screws 1/4"-28 (x inch lo	8	1
Pully Gear (hex bolt Pattern)	1	2
Pully Gear (shaft mount)	1	2
Linkage Assembly		
Bar Linkages	4	5
Shaft Collar	2	2
Bearing	2	4
Pully Gears	2	2
Pully Belt	1	1
DC Stepper Motor	1	3
Linkage Shaft	1	7
Wrist Assembly		
Mounting Joint	1	7
Wrist Motor Shaft	1	2
Gripper Pivot Shaft	1	6
Shaft Collar	2	1
DC Control Motor	1	1
DC Control Motor Mounting 5/32" Screw	1	1
Gripper Assembly		
Distal Gripper Fingers	2	5
Proximal Gripper Fingers	2	7
Medial Gripper Finger	2	5
Finger	2	4
Mounting Plate	1	10
Large Planar Gear	2	5
Small Planar Gear	1	2
1/4" Screws	12	7
5/16" Screws	2	3
Totals	65	99
Design for Assembly Metrics	**80.21845174**	

 Part Name	Number of Parts (Np)	Number of Interfaces (Ni)
Base Assembly		
Shoulder Motion Adapter Shaft OD 1"	1	6
Shoulder Mount	1	10
Shaft Collar ID 1"	1	3
Ball Bearing	4	2
DC Control Stepper motor	1	7
Pully Belt 1/4" thick	1	2
Button Head Cap Screws 1/4"-28 (x inch long) -Motor	4	3
Hex Nut	4	2
Pully Gear (hex bolt Pattern)	1	3
Pully Gear Wrist Motor Adapter	1	2
Bar Linkage Assembly		
Proximal Bar Linkage	1	12
Distal Bar Linkage	1	9
Shaft Collar ID 1"	4	2
Ball Bearing	5	2
Pully Gear (hex bolt Pattern)	2	3
Pully Belt	2	3
DC Control Stepper Motor	2	1
Elbow Motion Adapter Shaft OD 1"	2	5
Elbow Motor Adapter	2	2
Wrist Assembly		
Wrist Joint	1	4
Wrist Shaft Adapter OD 1"	1	6
Wrist Motor Shaft	1	2
DC Control Stepper Motor	1	6
Button Head Cap Screws 1/4"-28 (x inch long) -Motor	4	2
Gripper Assembly		
Regulator	1	1
Finger Mounting Plate	1	5
Pressure Tubes	1	1
Gripper Fingers	2	1
Totals	53	107
Design for Assembly Metrics	**75.30604225**	

Figure 14: DFA Complexity Comparison

The original robotic arm assembly had 65 parts total, with almost 50% of the parts being purchased hardware. One of the main goals of this project was to reduce the number of hardware parts in the assembly. This ultimately led to a decrease in the number of total parts and manufacturer secondary operations. The number of interfaces increased mainly in the base and bar linkage subassemblies. Condensing the shoulder mount increased the intricacy of the design in the base sub assembly. In addition, the proximal bar linkage became one of the most integral parts of the assembly because of the many interfaces in the shoulder assembly and close connection with the distal linkage.

The gripper assembly alone was reduced from 26 to 5 parts by implementing the pneumatic actuation technique. The original mechanical actuation method was greatly improved because the fingers are now able to be controlled more precisely and do not require the additional time and effort to assemble many small parts.

Theoretical & Practical Efficiency

Theoretical and practical efficiency was calculated to determine the efficiency of each part by considering the theoretical and practical minimum number of parts. The standardization of these parts was also explored to increase the utility of the same part. A comparison of the original and redesign matrix for this area is shown below.

Part Name	Part Can Be Standardized (if not already standard)	Cost (Low/Medium/High)	Practical Minimum Part
Base Assembly			
Mounting plate with pillow blocks	0	0	1
Shaft Collar	1	0	1
Set Screw Shaft Collar	1	0	0
Bearing	1	0	1
DC Stepper Motor	1	1	1
Pully Belt	1	0	1
Button Head Cap Screws 1/4"-28"	1	0	0
Pully Gear (hex bolt Pattern)	1	0	1
Pully Gear (shaft mount)	1	0	1
Linkage Assembly			
Bar Linkages	0	0	1
Shaft Collar	1	0	1
Bearing	1	0	1
Pully Gears	1	0	1
Pully Belt	1	0	1
DC Stepper Motor	1	1	1
Linkage Shaft	1	0	1
Wrist Assembly			
Mounting Joint	0	0	1
Wrist Motor Shaft	0	0	1
Gripper Pivot Shaft	0	0	1
Shaft Collar	1	0	1
DC Control Motor	1	1	1
DC Control Motor Mounting 5/32" Screw	1	0	0
Gripper Assembly			
Distal Gripper Fingers	0	0	0
Proximal Gripper Fingers	0	0	1
Medial Gripper Finger	0	0	1
Finger	0	0	0
Mounting Plate	0	0	1
Large Planar Gear	1	0	0
Small Planar Gear	1	0	0
1/4" Screws	1	0	0
5/16" Screws	1	0	0
Totals	14	2	18
Design for Assembly Metrics	**←Theor. Effy. Pract. Effy.→**		**27.7%**

Part Name	Theoretical Minimum Part	Part Can Be Standardized (if not already standard)	Cost (Low/Medium/High)	Practical Minimum Part
Base Assembly				
Shoulder Motion Adapter Shaft OD 1"	1	1	0	1
Shoulder Mount	1	0	0	1
Shaft Collar ID 1"	1	1	0	1
Ball Bearing	1	1	0	1
DC Control Stepper motor	1	1	1	1
Pully Belt 1/4" thick	1	1	0	1
Button Head Cap Screws 1/4"-28 (x inch long) -Motor	1	1	0	1
Hex Nut	1	1	0	1
Pully Gear (hex bolt Pattern)	1	1	0	1
Pully Gear Wrist Motor Adapter	0	0	0	1
Bar Linkage Assembly				
Proximal Bar Linkage	1	0	0	1
Distal Bar Linkage	1	0	0	1
Shaft Collar ID 1"	1	1	0	1
Ball Bearing	1	1	0	1
Pully Gear (hex bolt Pattern)	1	1	0	1
Pully Belt	1	1	0	1
DC Control Stepper Motor	1	1	1	1
Elbow Motion Adapter Shaft OD 1"	1	1	0	1
Elbow Motor Adapter	0	0	0	1
Wrist Assembly				
Wrist Joint	1	0	0	1
Wrist Shaft Adapter OD 1"	1	1	0	1
Wrist Motor Shaft	1	0	0	1
DC Control Stepper Motor	1	1	1	1
Button Head Cap Screws 1/4"-28 (x inch long) -Motor	1	1	0	1
Gripper Assembly				
Regulator	1	1	1	1
Finger Mounting Plate	1	0	0	1
Pressure Tubes	1	1	0	1
Gripper Fingers	1	0	0	1
Totals	21	15	3	23
Design for Assembly Metrics	**39.6%**	**←Theor. Effy. Pract. Effy.→**		**43.4%**

Figure 15: Theoretical and Practical Efficiency Comparison

Overall, our team successfully increased both efficiency measures in the redesign. The theoretical and practical number of parts increased in the redesign because of the intricacy of the design. By optimizing the functionality of each part and reducing the total number of parts, our team was able to almost double the efficiency measures. The number of standardized parts remained roughly the same at about 15 parts. This is because of the number of off-shelf hardware parts in the assembly.

Error Proofing

To better understand how easy, the parts will be assembled, error proofing was considered for the original and redesigned parts. The purpose of this category is to better understand how many parts could be assembled in an incorrect orientation or could be completely omitted from the product. By factoring this

 Part Name	Assemble Wrong Part/ Omit Part	Assemble Part Wrong Way Around
Base Assembly		
Mounting plate with pillow blocks	0	0
Shaft Collar	0	0
Set Screw Shaft Collar	0	0
Bearing	0	0
DC Stepper Motor	0	0
Pully Belt	0	0
Button Head Cap Screws 1/4"-28"	0	0
Pully Gear (hex bolt Pattern)	1	0
Pully Gear (shaft mount)	1	0
Linkage Assembly		
Bar Linkages	0	1
Shaft Collar	0	0
Bearing	0	0
Pully Gears	0	0
Pully Belt	0	0
DC Stepper Motor	0	0
Linkage Shaft	0	0
Wrist Assembly		
Mounting Joint	0	0
Wrist Motor Shaft	0	0
Gripper Pivot Shaft	0	0
Shaft Collar	0	0
DC Control Motor	0	0
DC Control Motor Mounting 5/32" Screw	0	0
Gripper Assembly		
Distal Gripper Fingers	1	1
Proximal Gripper Fingers	1	1
Medial Gripper Finger	1	1
Finger	0	0
Mounting Plate	0	0
Large Planar Gear	0	0
Small Planar Gear	0	0
1/4" Screws	0	0
5/16" Screws	0	0
Totals	5	4
Design for Assembly Metrics	0.47	

 Part Name	Assemble Wrong Part/ Omit Part	Assemble Part Wrong Way Around
Base Assembly		
Shoulder Motion Adapter Shaft OD 1"	0	0
Shoulder Mount	0	0
Shaft Collar ID 1"	0	0
Ball Bearing	0	0
DC Control Stepper motor	0	0
Pully Belt 1/4" thick	0	0
Button Head Cap Screws 1/4"-28 (x inch long) -Motor	0	0
Hex Nut	0	0
Pully Gear (hex bolt Pattern)	0	1
Pully Gear Wrist Motor Adapter	0	0
Bar Linkage Assembly		
Proximal Bar Linkage	0	0
Distal Bar Linkage	0	0
Shaft Collar ID 1"	0	0
Ball Bearing	0	0
Pully Gear (hex bolt Pattern)	0	0
Pully Belt	0	0
DC Control Stepper Motor	0	0
Elbow Motion Adapter Shaft OD 1"	0	0
Elbow Motor Adapter	0	0
Wrist Assembly		
Wrist Joint	0	0
Wrist Shaft Adapter OD 1"	0	0
Wrist Motor Shaft	0	0
DC Control Stepper Motor	0	0
Button Head Cap Screws 1/4"-28 (x inch long) -Motor	0	0
Gripper Assembly		
Regulator	0	0
Finger Mounting Plate	0	0
Pressure Tubes	0	0
Gripper Fingers	0	0
Totals	0	1
Design for Assembly Metrics	0.05	

Figure 16: Error Proofing Redesign Matrix

For error proofing, the index was reduced because of the reduction of the number of complex parts on the gripper assembly. The original mechanical finger actuation method had many parts that could easily be assembled incorrectly. Furthermore, the base assembly had two different pulley gears that could be assembled incorrectly. One of the goals of the redesign was to standardize the gears to avoid confusion on the assembly line.

Handling

Handling was determined by analyzing the difficulty for a manufacturer to grab a single component. By looking at the potential difficulty and hazards of handling of the components, this metric was analyzed comparing the original to the redesign as shown below.

Part Name 	Tangle, Nest, or Stick Together	Flexible, Fragile, Sharp or Slippery	Pliers, Tweezers, or Magnifying Glass Needed
Base Assembly			
Mounting plate with pillow blocks	0	0	0
Shaft Collar	0	0	0
Set Screw Shaft Collar	0	0	0
Bearing	0	0	0
DC Stepper Motor	0	0	0
Pully Belt	0	0	0
Button Head Cap Screws 1/4"-28"	0	0	0
Pully Gear (hex bolt Pattern)	0	0	0
Pully Gear (shaft mount)	0	0	0
Linkage Assembly			
Bar Linkages	0	0	0
Shaft Collar	0	0	0
Bearing	0	0	0
Pully Gears	0	0	0
Pully Belt	0	0	0
DC Stepper Motor	0	0	0
Linkage Shaft	0	0	0
Wrist Assembly			
Mounting Joint	0	0	0
Wrist Motor Shaft	0	0	0
Gripper Pivot Shaft	0	0	0
Shaft Collar	0	0	0
DC Control Motor	0	0	0
DC Control Motor Mounting 5/32" Screw	0	0	0
Gripper Assembly			
Distal Gripper Fingers	0	0	0
Proximal Gripper Fingers	0	0	0
Medial Gripper Finger	0	0	0
Finger	0	0	0
Mounting Plate	0	0	0
Large Planar Gear	0	0	0
Small Planar Gear	0	0	0
1/4" Screws	0	0	0
5/16" Screws	0	0	0
Totals	0	0	0
Design for Assembly Metrics	0.00		

Part Name 	Tangle, Nest, or Stick Together	Flexible, Fragile, Sharp or Slippery	Pliers, Tweezers, or Magnifying Glass Needed
Base Assembly			
Shoulder Motion Adapter Shaft OD 1"	0	0	0
Shoulder Mount	0	0	0
Shaft Collar ID 1"	0	0	0
Ball Bearing	0	0	0
DC Control Stepper motor	0	0	0
Pully Belt 1/4" thick	0	0	0
Button Head Cap Screws 1/4"-28 (x inch long) -Motor	0	0	0
Hex Nut	0	0	0
Pully Gear (hex bolt Pattern)	0	0	0
Pully Gear Wrist Motor Adapter	0	0	0
Bar Linkage Assembly			
Proximal Bar Linkage	0	0	0
Distal Bar Linkage	0	0	0
Shaft Collar ID 1"	0	0	0
Ball Bearing	0	0	0
Pully Gear (hex bolt Pattern)	0	0	0
Pully Belt	0	0	0
DC Control Stepper Motor	0	0	0
Elbow Motion Adapter Shaft OD 1"	0	0	0
Elbow Motor Adapter	0	0	0
Wrist Assembly			
Wrist Joint	0	0	0
Wrist Shaft Adapter OD 1"	0	0	0
Wrist Motor Shaft	0	0	0
DC Control Stepper Motor	0	0	0
Button Head Cap Screws 1/4"-28 (x inch long) -Motor	0	0	0
Gripper Assembly			
Regulator	0	0	0
Finger Mounting Plate	0	0	0
Pressure Tubes	1	0	0
Gripper Fingers	0	0	0
Totals	1	0	0
Design for Assembly Metrics	0.05		

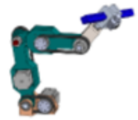
Figure 17: Handling Metric Comparison

For the original design a handling index of 0.00 was calculated and increased to 0.05. The original design did not present any handling issues. All the parts are robust and easy to handle for the assembler. There was a slight increase in this metric due to the redesign in the gripper assembly by including the potential tangling of the pressure tubes.

Insertion

Insertion is a DFA metric that explores the difficulty of assembly of the components. Some key considerations in this section are alignment, holding down the part for assembly, part insertion resistance, and potential obstruction or access to key features. A table comparing the original to the redesign of the robotic arm is shown below.

Part Name	Difficult to Align/ Locate	Holding Down Required	Resistance to Insertion	Obstructed Access/ Visibility
Base Assembly				
Mounting plate with pillow blocks	0	1	0	0
Shaft Collar	1	0	0	0
Set Screw Shaft Collar	1	0	0	1
Bearing	1	0	0	1
DC Stepper Motor	0	0	0	0
Pully Belt	0	0	0	0
Button Head Cap Screws 1/4"-28"	0	0	0	0
Pully Gear (hex bolt Pattern)	0	0	0	0
Pully Gear (shaft mount)	0	0	0	0
Linkage Assembly				
Bar Linkages	1	1	1	0
Shaft Collar	1	0	0	0
Bearing	1	0	0	0
Pully Gears	0	0	0	0
Pully Belt	0	0	0	0
DC Stepper Motor	0	0	0	0
Linkage Shaft	1	0	0	0
Wrist Assembly				
Mounting Joint	0	0	0	0
Wrist Motor Shaft	0	0	1	1
Gripper Pivot Shaft	0	0	0	0
Shaft Collar	0	0	0	0
DC Control Motor	0	1	0	1
DC Control Motor Mounting 5/32" Screw	1	0	0	0
Gripper Assembly				
Distal Gripper Fingers	1	1	1	0
Proximal Gripper Fingers	1	1	1	0
Medial Gripper Finger	1	1	1	0
Finger	1	1	1	0
Mounting Plate	0	1	0	0
Large Planar Gear	1	0	0	0
Small Planar Gear	1	0	0	0
1/4" Screws	1	0	0	0
5/16" Screws	1	0	0	0
Totals	10	7	6	2
Design for Assembly Metrics		1.32		



Part Name	Difficult to Align/ Locate	Holding Down Required	Resistance to Insertion	Obstructed Access/ Visibility
Base Assembly				
Shoulder Motion Adapter Shaft OD 1"	1	0	0	0
Shoulder Mount	1	1	0	0
Shaft Collar ID 1"	1	0	0	0
Ball Bearing	1	0	1	0
DC Control Stepper motor	0	0	0	0
Pully Belt 1/4" thick	0	0	0	0
Button Head Cap Screws 1/4"-28 (x inch long) -Motor	0	0	0	0
Hex Nut	0	0	0	0
Pully Gear (hex bolt Pattern)	0	0	1	1
Pully Gear Wrist Motor Adapter	0	0	0	0
Bar Linkage Assembly				
Proximal Bar Linkage	0	1	1	0
Distal Bar Linkage	0	1	1	0
Shaft Collar ID 1"	1	0	0	0
Ball Bearing	1	0	0	0
Pully Gear (hex bolt Pattern)	0	0	0	0
Pully Belt	0	0	0	0
DC Control Stepper Motor	0	0	1	0
Elbow Motion Adapter Shaft OD 1"	0	0	1	0
Elbow Motor Adapter	0	0	1	0
Wrist Assembly				
Wrist Joint	0	0	0	0
Wrist Shaft Adapter OD 1"	0	0	0	0
Wrist Motor Shaft	0	0	0	0
DC Control Stepper Motor	0	0	1	1
Button Head Cap Screws 1/4"-28 (x inch long) -Motor	1	0	1	1
Gripper Assembly				
Regulator	0	1	0	1
Finger Mounting Plate	0	0	0	0
Pressure Tubes	0	0	0	0
Gripper Fingers	0	0	0	0
Totals	3	3	8	4
Design for Assembly Metrics		0.86		

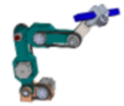
Figure 18: Insertion DFA Metric Comparison

The insertion index was reduced from 1.32 to 0.82. This was largely due to the potential alignment issues in the gripper assembly including the various finger joints. By removing the mechanical finger assembly, our team was also able to decrease the amount of holding required and resistance to insertion of the screws in the assembly. The redesign did pose some obstruction issues with the motor at the wrist. The motor is positioned inside the wrist joint which would be more difficult to assemble than if the motor was freely outside the wrist joint on the linkage.

Secondary Operations

The final subcategory of the DFA analysis is secondary operations which includes the number of times the workpiece must be orientated, and whether the parts may need a secondary operation for securing the assembly. The results of the original and redesign are shown in the figure below.

Part Name	Re-orient Workpiece	Screw, Drill, Twist, Rivet, Bend, or Crimp	Weld, Solder, or Glue	Paint, Lube, Heat, Apply Liquid or Gas	Test, Measure or Adjust
Base Assembly					
Mounting plate with pillow blocks	0	1	0	0	0
Shaft Collar	0	0	0	0	0
Set Screw Shaft Collar	0	0	0	0	0
Bearing	0	0	1	0	0
DC Stepper Motor	0	1	0	0	0
Pully Belt	0	0	0	0	0
Button Head Cap Screws 1/4"-28"	0	1	0	0	0
Pully Gear (hex bolt Pattern)	0	0	0	0	0
Pully Gear (shaft mount)	0	0	0	0	0
Linkage Assembly					
Bar Linkages	1	0	0	0	0
Shaft Collar	0	0	0	0	0
Bearing	0	0	0	0	0
Pully Gears	0	0	0	0	0
Pully Belt	0	0	0	0	0
DC Stepper Motor	0	0	1	0	0
Linkage Shaft	0	0	0	0	0
Wrist Assembly					
Mounting Joint	0	0	0	0	0
Wrist Motor Shaft	0	0	0	0	0
Gripper Pivot Shaft	0	0	0	0	0
Shaft Collar	0	0	0	0	0
DC Control Motor	1	1	0	0	0
DC Control Motor Mounting 5/32" Screw	1	1	0	0	0
Gripper Assembly					
Distal Gripper Fingers	0	1	0	0	0
Proximal Gripper Fingers	0	1	0	0	0
Medial Gripper Finger	0	1	0	0	0
Finger	0	1	0	0	0
Mounting Plate	0	1	0	0	0
Large Planar Gear	0	0	0	0	0
Small Planar Gear	0	0	0	0	0
1/4" Screws	0	1	0	0	0
5/16" Screws	0	1	0	0	0
Totals	3	8	1	0	0
Design for Assembly Metrics			0.63		



Part Name	Re-orient Workpiece	Screw, Drill, Twist, Rivet, Bend, or Crimp	Weld, Solder, or Glue	Paint, Lube, Heat, Apply Liquid or Gas	Test, Measure or Adjust
Base Assembly					
Shoulder Motion Adapter Shaft OD 1"	0	1	0	0	0
Shoulder Mount	0	0	0	0	0
Shaft Collar ID 1"	0	0	0	0	0
Ball Bearing	0	0	0	0	0
DC Control Stepper motor	0	1	0	0	0
Pully Belt 1/4" thick	0	0	0	0	0
Button Head Cap Screws 1/4"-28 (x inch long) -Motor	0	1	0	0	0
Hex Nut	0	1	0	0	0
Pully Gear (hex bolt Pattern)	0	0	0	0	0
Pully Gear Wrist Motor Adapter	0	0	0	0	0
Bar Linkage Assembly					
Proximal Bar Linkage	0	0	0	0	0
Distal Bar Linkage	0	0	0	0	0
Shaft Collar ID 1"	0	0	0	0	0
Ball Bearing	0	0	0	0	0
Pully Gear (hex bolt Pattern)	0	0	0	0	0
Pully Belt	0	0	0	0	0
DC Control Stepper Motor	0	0	0	0	0
Elbow Motion Adapter Shaft OD 1"	0	0	0	0	0
Elbow Motor Adapter	0	0	0	0	0
Wrist Assembly					
Wrist Joint	0	0	0	0	0
Wrist Shaft Adapter OD 1"	0	0	0	0	0
Wrist Motor Shaft	0	0	0	0	0
DC Control Stepper Motor	0	1	0	0	0
Button Head Cap Screws 1/4"-28 (x inch long) -Motor	0	1	0	0	0
Gripper Assembly					
Regulator	1	0	1	0	0
Finger Mounting Plate	0	0	0	0	0
Pressure Tubes	0	1	0	0	0
Gripper Fingers	0	0	1	0	0
Totals	1	5	2	0	0
Design for Assembly Metrics			0.38		

Figure 19: Secondary Operations DFA Metric Comparison

Overall, the redesign metric decreased by 0.25 in this category. This is largely due to the reduction of screw operations in the gripper subassembly. The redesign does present an additional adhesive step for the regulator and gripper fingers. The final redesign also includes merging the pulley with the linkage into one part in the linkage subassembly. This part reduction also reduced the number of secondary operations for securing the stepper motors.

Initial Design Concepts

Gripper in Drum Concept

To concept an early idea for the gripper, the CU Rover Team had developed a cad model for an inexpensive cost robotic arm of stepper motors that are belt driven with a gripper for grasping objects. This concept had been to show how the gripper would be two-pronged and actuate based on one motor. This is revealed by the motor housing through the transparent image of this gripper shown.

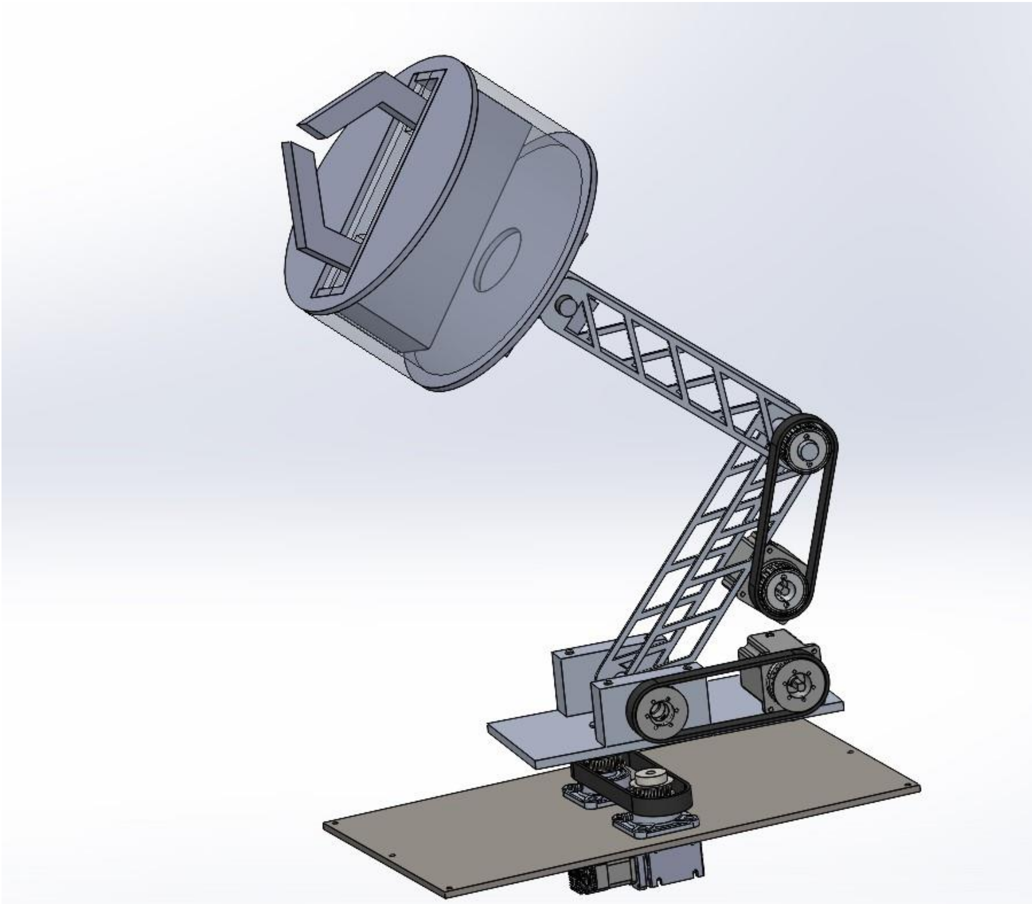


Figure 20: Gripper in Drum Concept

Gripper in Rigid Finger Concept

To develop a gripper with well weight distribution, our team implemented this rigid finger concept into the design. The gripper that is shown is driven by one stepper motor with two meshing gears. The two gears actuate the gripper to perform at an identical rotational speed. This gripper configuration has a modular fitting to have a gripper for multiple different functions.

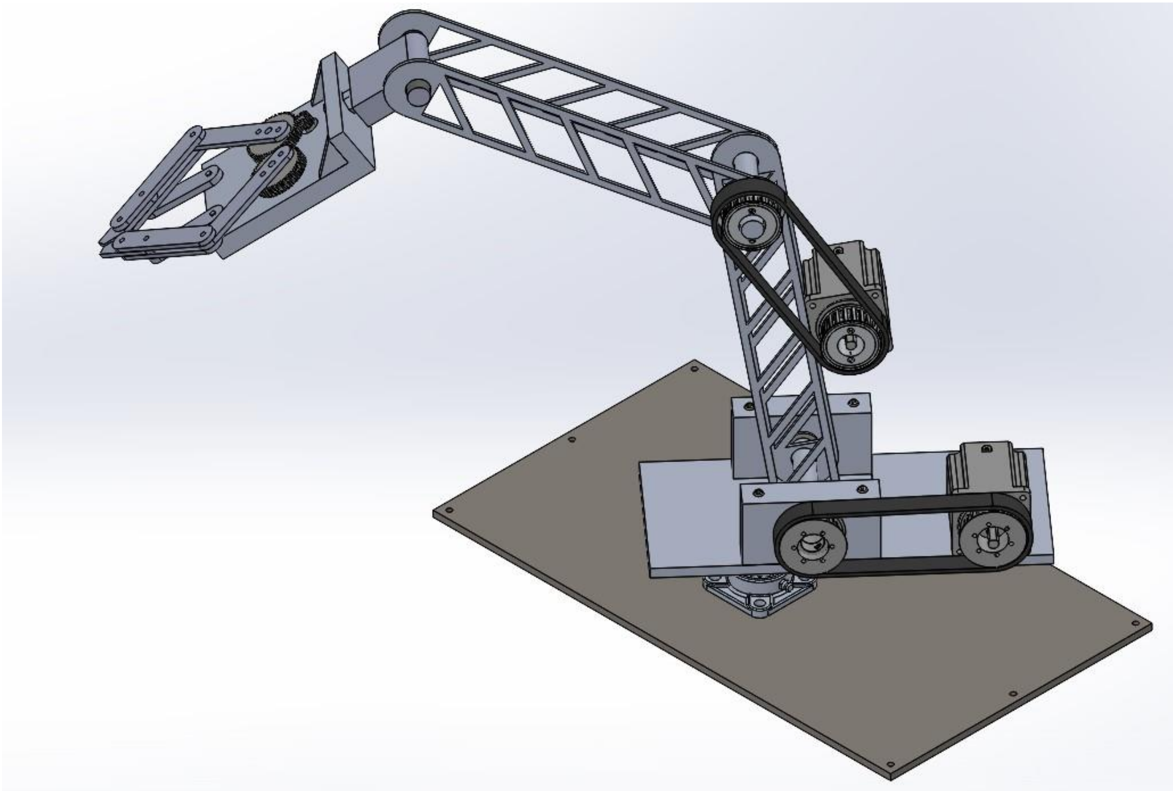


Figure 21: Gripper in Rigid Finger Concept

Solid Linkage

A final concept is to switch from double linkages to solid linkages. Having one linkage to be secure onto both sides of a shaft will increase the structural integrity of this assembly. This thickened linkage can support the stepper motors within the assembly as shown.

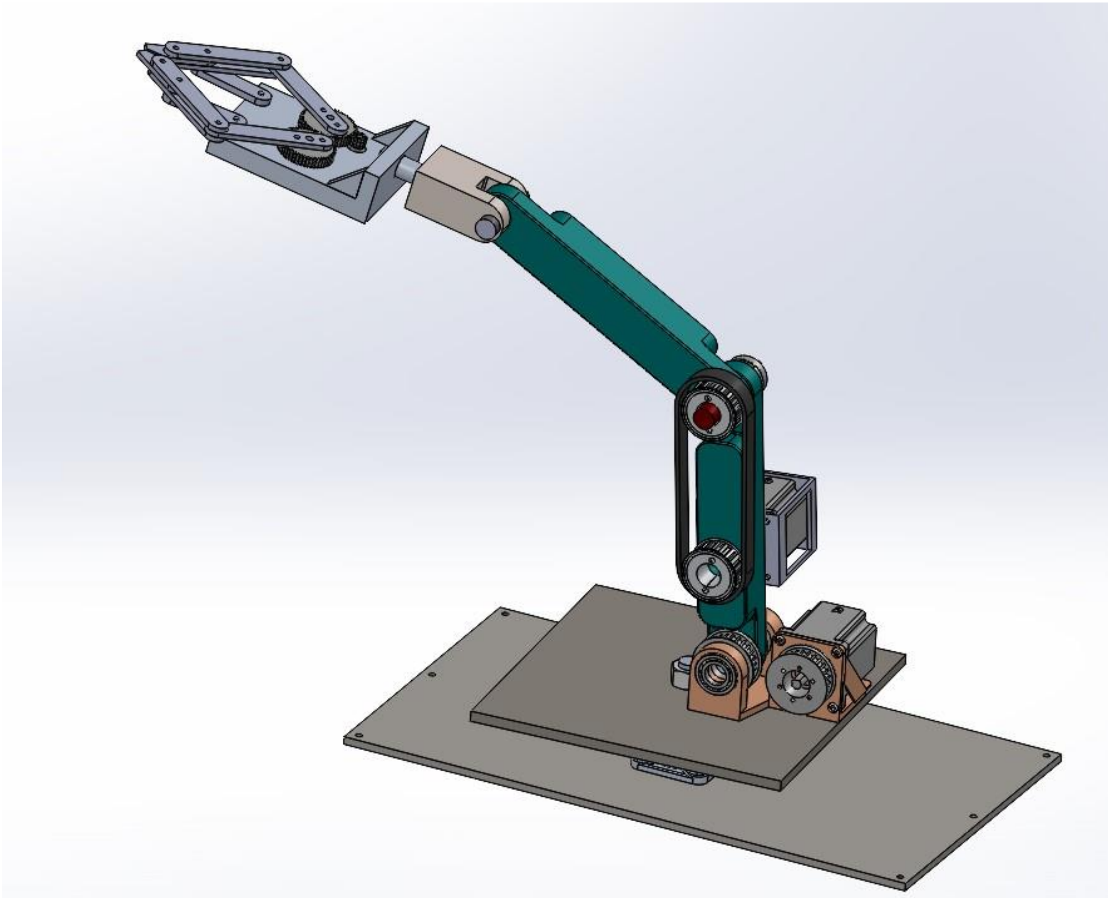


Figure 22: Solid Linkage's Concept

Rigid Vs. Soft Gripper

When dealing with a robotic arm for Mars missions, there is a chance of collecting fragile objects. Therefore, our team has designed this gripper to be modular and developed a soft robotic actuator/soft gripper. The image on the right is this soft gripper displayed. The two ends of the gripper of soft fingers with multiple air channels. These channels fill to a certain pressure and allow the gripper to flex. When in the fully flexed position, this gripper will be able to grab fragile objects that could be stored as samples for the Rover missions.

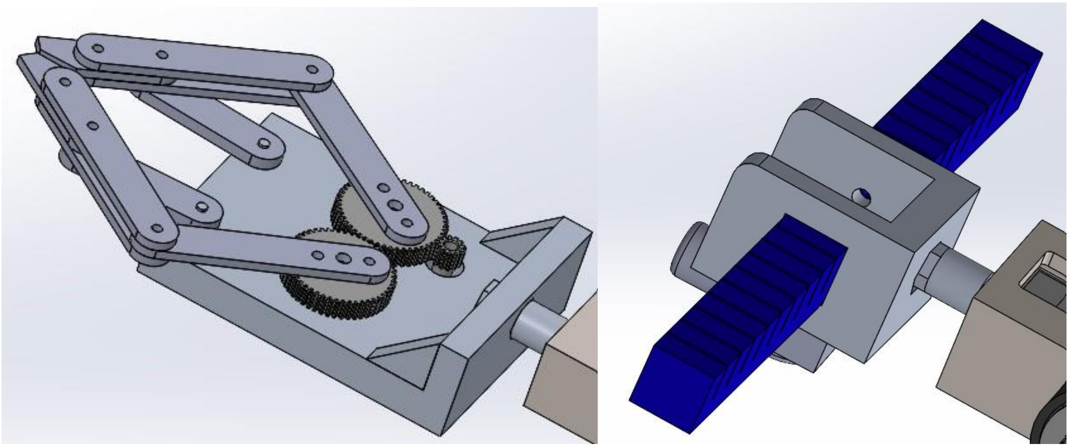


Figure 23: Gripper Assembly: Original Design (left), Redesign (right)

Motor Pockets in Linkages

In a careful evaluation of fasteners and fixtures for the stepper motors, it has been ideated to develop linkages with pockets for the motors to be held fixed along the center of the links. This idea has allowed our team to have stepper motors at all desired degrees of freedom in adding an additional stepper motor to the top linkage. With this pocket concept, the wrist is now able to rotate on the shaft connecting to the upper linkage without concern of accounting for large metrics for the moment of inertia with respect to the position of the stepper motors attached.

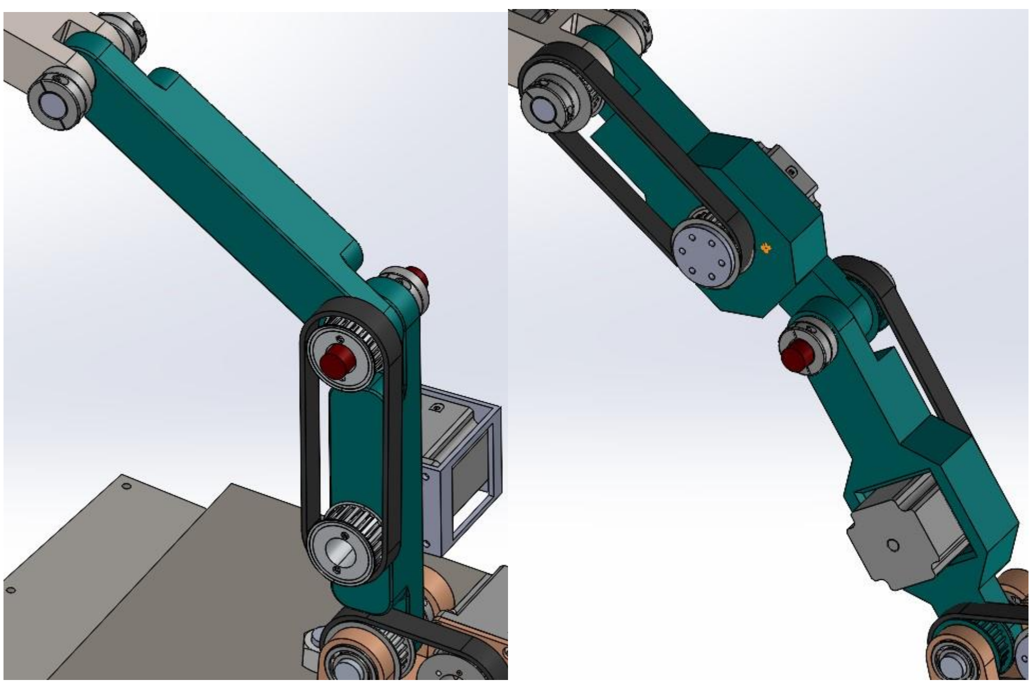


Figure 24: Bar Linkage Assembly: Original Design (left), Redesign (right)

Size Reduction in Base Mount

The base mount had been completely redesigned from the original idea. On the left is an assembly of the base mount with two pillow blocks to mount bearings that are fastened to the base plate. Due to the position of the pillow blocks, the original belt-motor drive has to be extended a distance away front the shaft. In careful evaluation, our team decided that extended belts will result in more complications and errors in assembly. With a high rate of failure. Therefore, the base mount had been redesigned into one investment cast component for the assembly. The redesign resulted in a short distance between pulleys. Have fixed distances between the pulleys between errors in installing rubber belts to actuate the arm. The new base mount also has stepper mounting features built in and self-locating features added for assembly. Room to press fit bearings into the new base mount is also included.

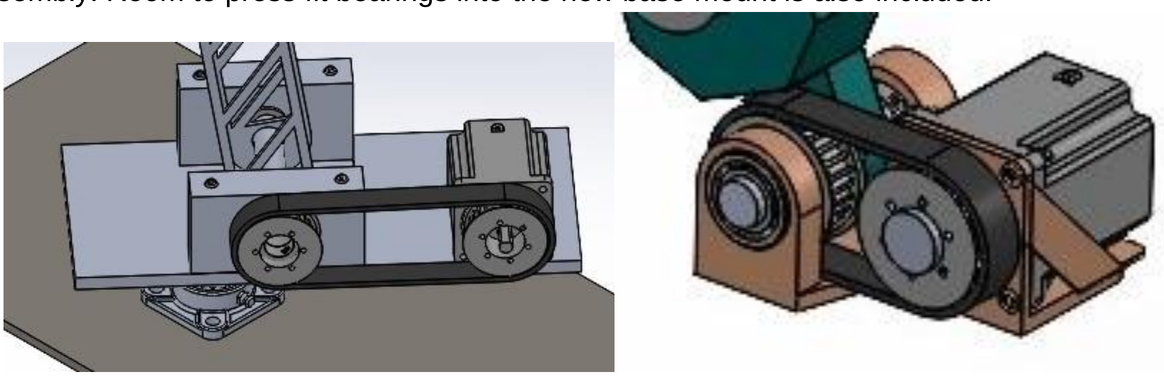


Figure 25: Base Assembly: Original Design (left), Redesign (right)

Testing Plan

Manipulation

The Arm Assembly will be tested with respect to the mission that it will complete the University Rover Challenge (URC). The URC will take on four missions: the Science, Extreme Retrieval and Delivery, Equipment Servicing, and Autonomous Navigation missions. Three out of the four will have their own individual challenges that will integrate the use of the robotic arm.

Science Mission:

This mission will take on data collection and test sampling of material found at the location site of the challenge, which is an open desert. The robotic arm must be able to grab samples of rock and debris to set into a data collection box to be evaluated to indicate material properties. Samples will have to be well controlled and placed items into the data collection box to be understood. For testing purposes, the arm will practice grasping objects and placing them into a container for trial.

Extreme Retrieval and Delivery:

Within this mission, there will be objects that will have to be carried to a separate location zone. Objects will be rocks and objects connected to the rope to deliver. Our arm assembly must have good structural integrity to be able to deliver objects and displace them to a secure location. Prior to the competition at CU, our team will test by having weights on a rope and attempting to drag them over a certain distance of rough terrain (grass and sand).

Equipment Servicing:

The final mission for the arm assembly is to use tools for disassembling a mechanical system. The objective is to push buttons, flip switches and turn knobs. Our gripper will need to grasp and control tooling, as screwdrivers and hammers, to complete parts of this mission. Within the Idea Forge/ITLL our team would practice rotations of a screwdriver and the use of hammers to test applications of repairing a mechanical system.

Autonomous Navigation:

(This mission will not have robotic arm applications).

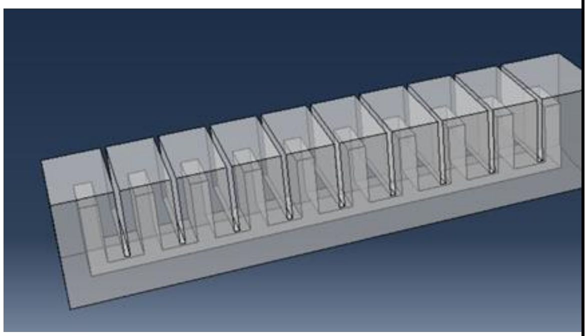
Gripper Simulation and Testing

To close the loop on any actuator-controller configuration, sensors must be used to provide feedback data to the controller. In our testing, the actuator will be fabricated via FDM 3D printing on the MakerGear M3 printer platform available in our university. We will use a 0.4mm nozzle to distribute 95A shore hardness TPU. This filament material exhibits increased print reliability yet obtains deflection characteristics like other 80A shore hardness TPU filaments for our given actuator geometry.

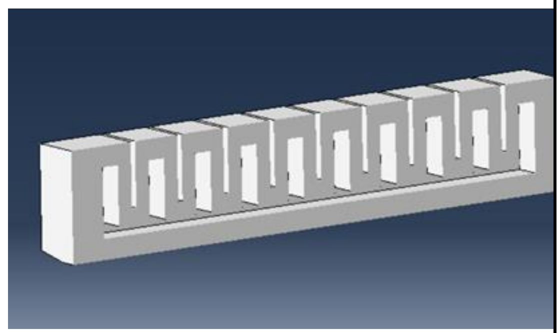
Once we have 3D printed our gripper finger, we will test the accuracy of grasping by validating the bending of the actuator with our FEA results given below. We can measure the bending through analog values using a data acquisition setup like Lab Jack. With the well-defined material properties, it is possible to predict the current state of the actuator geometry using node locations, and predictions of the intermediary space between nodes using the lowest energy states of the material. A pressure transducer will be required that will interface with the DAQ and the actuator and give us plots in MATLAB. This will help us build a relationship between the input pressure of the actuator (pressure output for transducer) and degrees of flexion sustained within the actuator.

Finite Element Method

Modeling and Meshing: The soft gripper finger has 10 inner gas chambers and a channel through one end through the last chamber in which pressurized air is supplied through the pressure regulator attached below the mounting plate. Because of this pneumatic design (Fig26), the actuation causes the gripper to bend just like we bend a human finger. The bellows in the figure shown below are analogous to our knuckles and allow the gripper to grasp objects efficiently. The design was imported from SolidWorks to ABAQUS CAE viewport. Meshing was done using tetrahedral elements for non-linear geometry (hyper elastic material) (Fig27).



(a) Transparent view of inner gas chambers



(b) Section view of the chambers

Figure 26: Soft Gripper ABAQUS CAE viewport

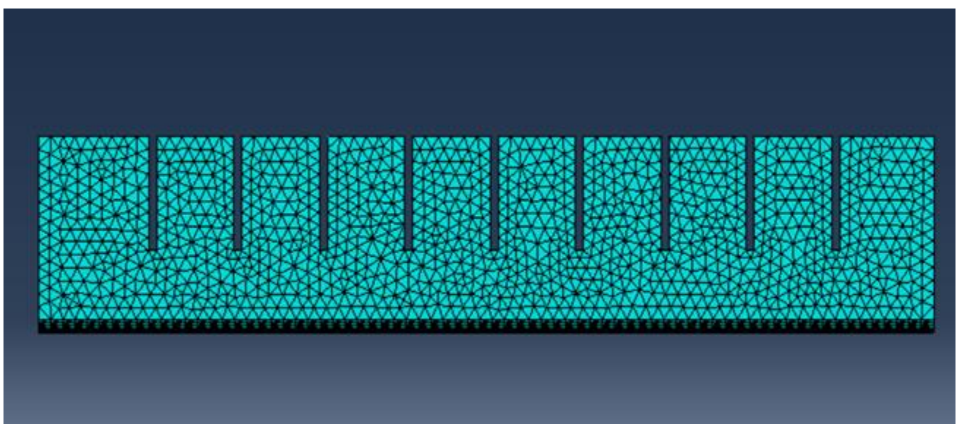


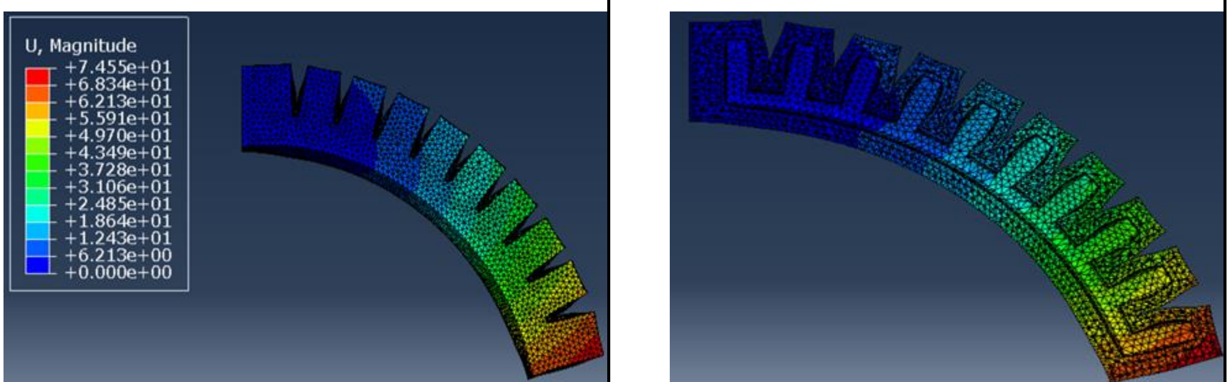
Figure 27: Mesh

The material model for TPU used here was Yeoh with the following coefficients (Fig28). The Yeoh hyper elastic material model is a phenomenological model for the nearly incompressible and non-linear elastic materials. The model is based on Rivlin's observation that elastic properties of rubber may be described using a strain energy density function which is a power series for the strain invariants I_1, I_2 , I_3 . Based on previous research [X], the NinjaFlex material (TPU in our case) is more suitable to the Yeoh model (units are in GPa):

C10	C20	C30	D1
0.11	0.02	0	0

Figure 28: Material Constants

Results: Since it is made of a hyper elastic material, it has large deflection (Fig29(a)) and there is bulging/inflation of the bellows because of increase in pressure inside the chambers (Fig29(b)).

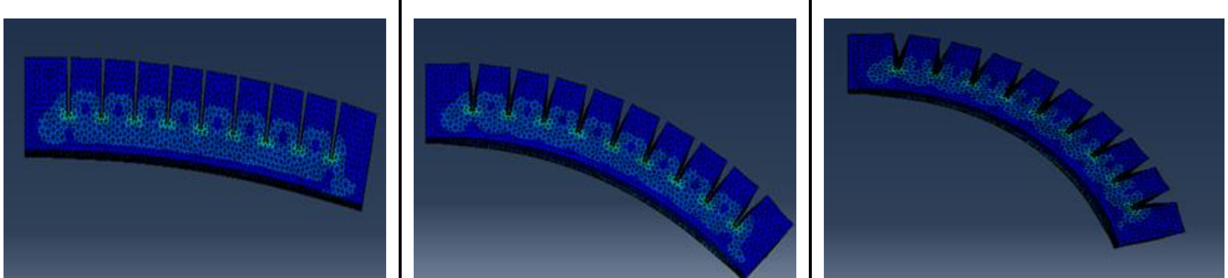


(a) Large displacement

(b) Inflation of the gas chambers

Figure 29: Deflection

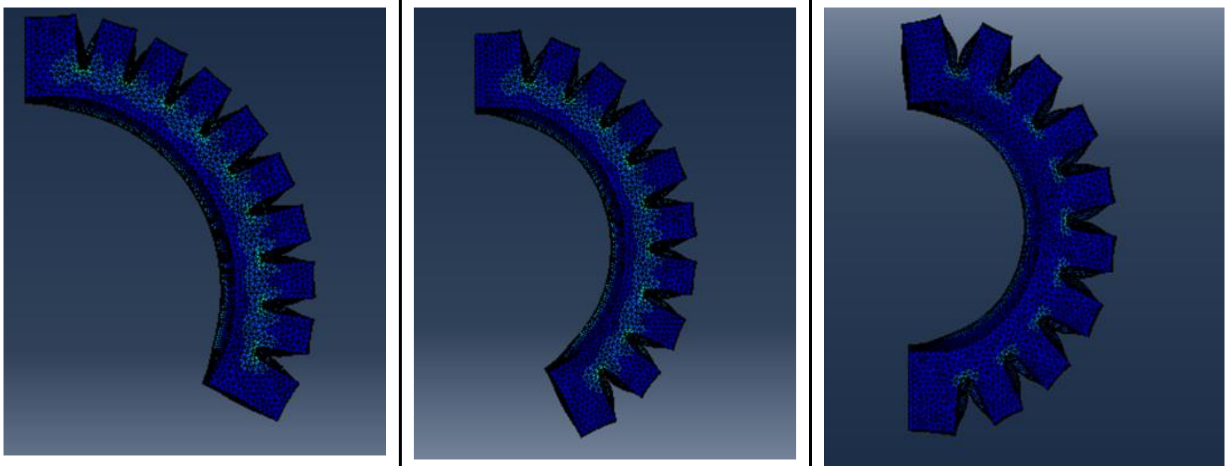
As you can see from Fig30, the bending angle increases with increase in pressure and the actuator bends in a circular trajectory. As pressure increased from 10000 Pa to 90000 Pa, the displacement of the monitor edge in both x-axis and y-axis decreased. As the pressure increases, the displacement in x direction still decreases. However, the displacement in y direction increases since the bending actuator starts becoming a circle.



10 kPa

30kPa

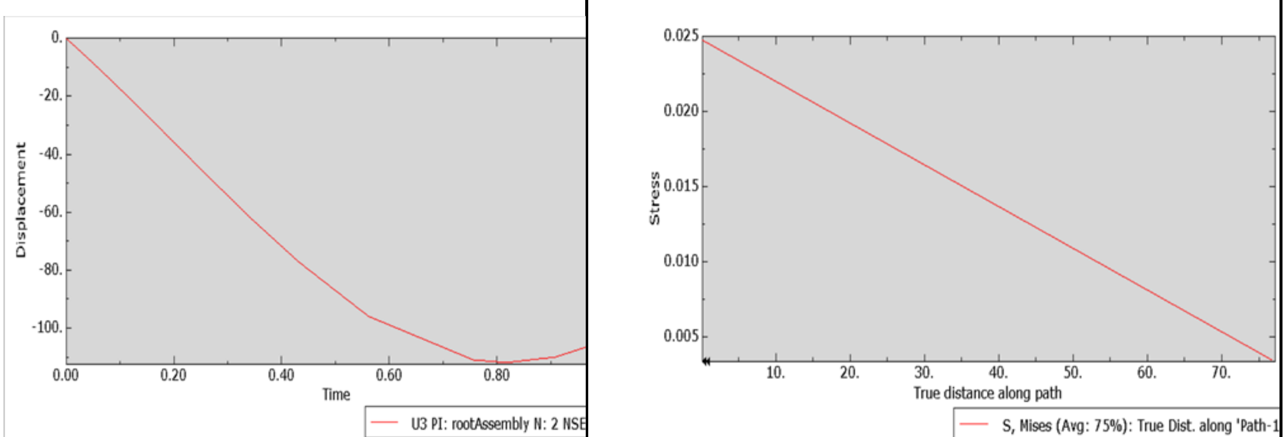
50kPa



70kPa | 90kPa | 110kPa

Figure 30: Bending at different pressures

Fig31 shows the angular displacement (theta) with time and stress along the length of the actuator just below the bellows. As we can see, the angular displacement is nonlinearly increasing and after a certain saturation point increases again as the actuator hits the semi-circle. The stress however is linearly decreasing as we move away from the Encastre point at which the channel starts since the path chosen is just below the center of pressure line (with zero deflection and stress). As we move away from the COP, the more non-linear the stress curve will become.



(a) Angular Displacement (rad)

(b) Stress along the length of actuator (MPa)

Figure 31: Results of Angular Displacement and Stress Along Actuator

Materials and Manufacturing Analysis

Material Analysis

There are two rolls we need materials to fill for custom parts in this product. First is structural. The second is a flexible material for the gripper actuator.

Structural Material Selection

We consider structural materials from a cost to weight ratio and from a cost per volume perspective. We considered cost to weight because we assume our device will be launched from earth to mars, secondly, we consider cost per unit volume because the device must be affordable. The previous rover team had not decided on its material selection however we will assume aluminum as a starting material.

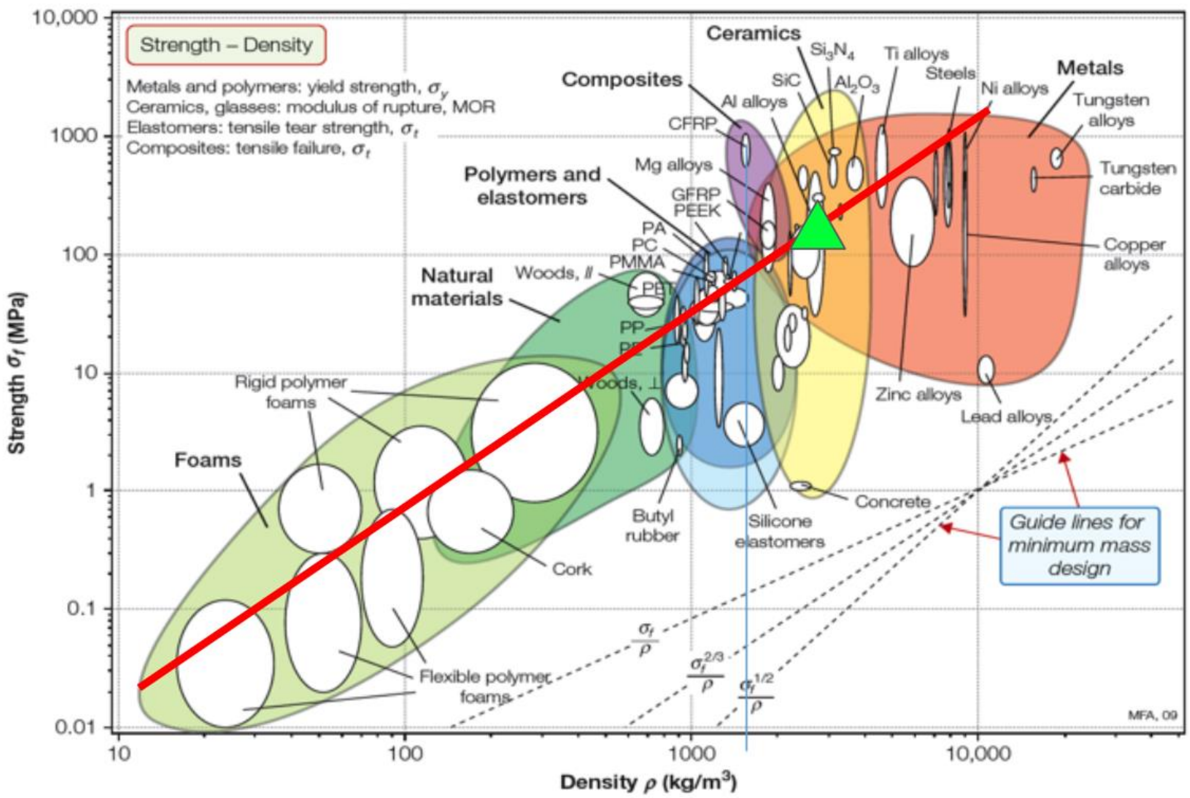


Figure 32: Failure Strength vs Material Density Selected Material Aluminum (Green Triangle)

Here we can see that Aluminum (green triangle) is a good material choice only beat out significantly by composites for this metric. However, we also should consider the viability of composites for custom manufacturability and cost of material.

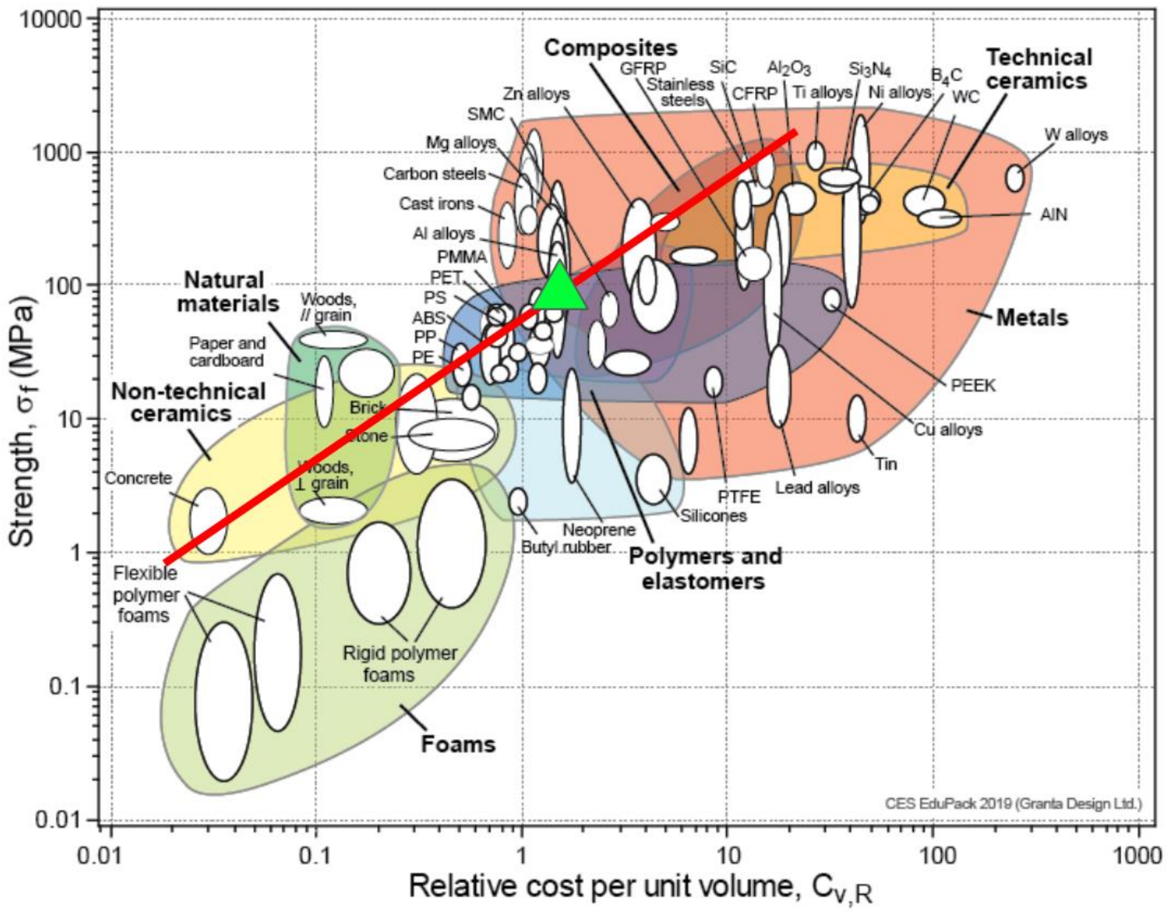


Figure 33: Failure Strength vs Material Cost per Volume Selected Material Aluminum (Green Triangle)

We are going to be optimistic and say that if we are selling 100,000 units of this robotic arm that the cost of lifting mass to mars is significantly more affordable than it is today. Therefore, we must consider the relative cost of the material as a relevant factor. Here we can see that despite composites beating out aluminum in strength vs density it loses when it comes to cost per unit volume. In addition, composites are not as compatible with complex geometry manufacturing methods that we would like to utilize to reduce part count and improve ease of assembly. Therefore, for the structural and mounting components this team selected an aluminum alloy, for its strength density and relative cost. There is myriad of other reasons to pick aluminum over composites like its retention of strength under large temperature changes and its fracture toughness; however, we will not get too deep into that here.

Flexible Gripper Actuator Material Selection

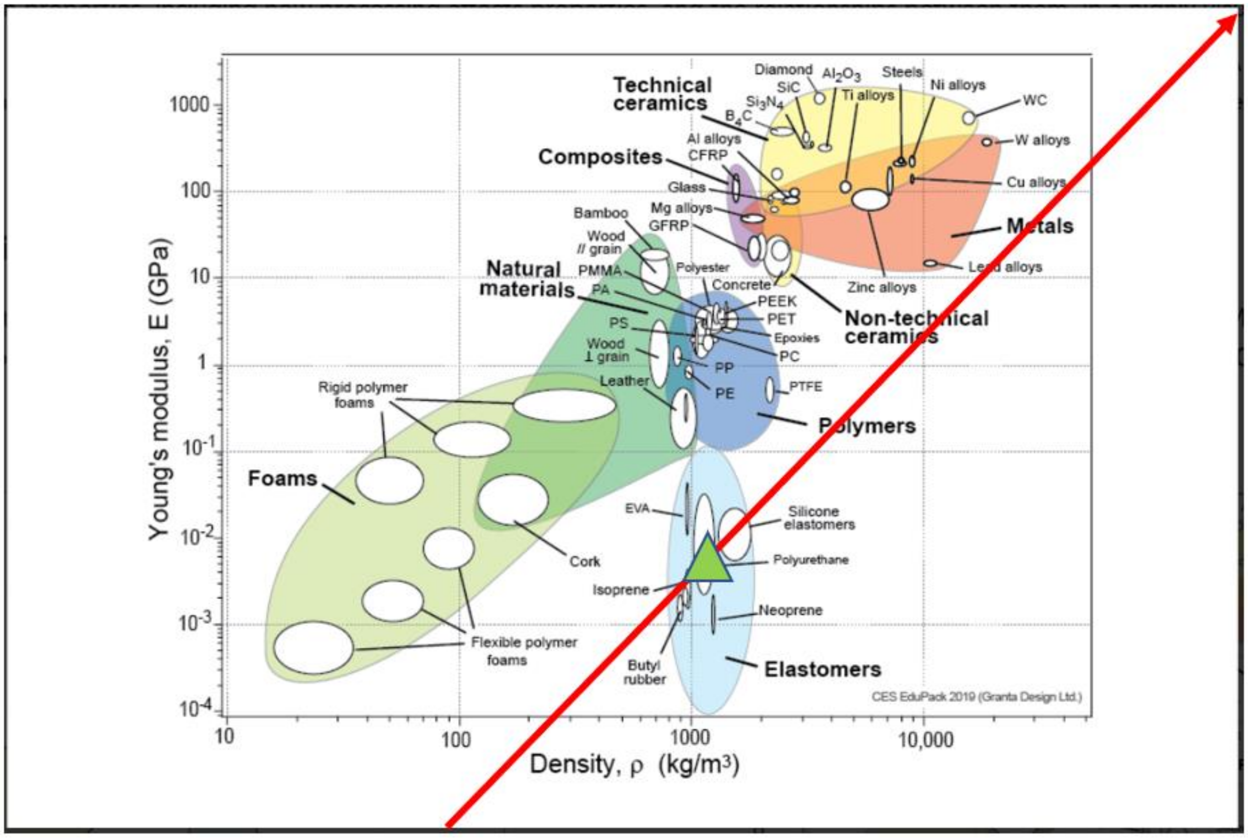


Figure 34: Young's modulus vs Density Selected Material TPU (Green Triangle)

Inspired by biology, researchers aim to develop soft bodied programmable motion to combine natural compliance with controllable actuation. One of the long-standing challenges has been the lack of easily processed robust soft actuators with high strain density. We have used thermoplastic polyurethane, commercially available as NinjaFlex (NinjaTek, USA) to 3D print our soft gripper finger. This material combines a high strain (up to 900%) and correspondingly high stress (up to 80-150MPa) with low density (1.005 g/cm3), as we can see from the Ashby Chart. It can lift and grasp high payloads of 5-7kg. For our simulation, we have used the Yeoh coefficients from previous research that matches this Ashby chart. The density for our ABAQUS model is 1.049 g/cm3 and the coefficients C10 and C20 are 110MPa and 20 MPa respectively.

Process Selection

The team decided to use Investment casting for all the custom metal components for this product. There are several reasons. Firstly, the components are relatively complex. They include built in pulley gears, self-locating mounting geometry, and structural components. We selected investment casting over other forms of casting because the high degree of dimensional accuracy was desirable to be able to press fitting bearings without significant secondary manufacturing processes. Several screw holes to mount the stepper motors were also needed and these also needed to have relatively high tolerancing. The device also needed to be relatively strong and lightweight, which necessitated Metal construction which helped us eliminate many other processes. We eliminated reductive processes such as milling because of the material waste involved and the additional man hours required for this method. We estimated some parts could cost as much as double if we had used a reductive process.

The thermoplastic polyurethane (TPU) Fingers for the gripper were surprisingly FDM 3D printed. It turned out that to create this geometry it was helpful to 3D print it and shockingly the capital cost per printer while slow was so low and required an operator for only a fraction of the operating time. This all meant that FDM 3D printing, while possibly not the most affordable method, was relatively affordable and did not contribute a large percentage to the final product's cost, each finger coming in at just $2 USD.

Economic Analysis of Product

Custom Parts

An in-depth economic analysis was carried out for all custom components that could not be bought off the shelf for this device. We assumed a target production quantity of 100,000 units. The analysis shows that most of the cost for the metal components is composed of material and labor costs. The labor is largely spent on cleaning the plaster molds off the finished details of the metal pieces like from the pulley gear cavities and mounting holes for the motors. It is notable that the capital cost per unit is low due to the high unit count. All the tables below can be found in their full form in the appendix.

The TPU polymer pneumatic fingers were modeled with FDM 3D printing. We assumed each 3D printer would cost $150 and take five hours to produce a pair of TPU pneumatic gripper fingers but that only a fraction of that load factor time would require the intervention of a laborer, scraping the parts off the build plates and checking for failed prints.
A sanity check for calculated part manufacturing costs is included in all summary tables at the bottom in blue using the 1:3:9 rule of thumb. We see that the calculated costs are relatively like the rule of thumb values. See the Appendix for these values.

Table 2: Original Design Custom Part Manufacturing Economic Analysis Summary (part 1)

			Part Name:			
Cost Element	Symbol	Unit	Mounting Plate	Bar Linkages (Plate)	Wrist Joint	Proximal Finger
Total Unit Cost (USD)			8.12	10.36	8.64	1.78
Qb Units Produced to Break Even			471.90	3160.39	7954.83	4978.00

Table 3: Original Design Custom Part Manufacturing Economic Analysis Summary (part 2)

			Part Name:		
Cost Element	Symbol	Unit	Medial Finger	Distal Finger	Mounting Plate (grippers)
Total Unit Cost (USD)			1.72	2.12	3.21
Qb Units Produced to Break Even			5626.89	3046.04	1362.96

Table 4: Redesigned Custom Part Manufacturing Economic Analysis Summary (part 1)

			Part Name:			
Cost Element	Symbol	Unit	Shoulder Mounting Plate	Bar Linkage	Wrist Joint	Shoulder Mount
Total Unit Cost (USD)			7.50	15.03	8.16	7.89
Qb Units Produced to Break Even			10136.66	2710.78	8181.41	8517.32

Table 5: Redesigned Custom Part Manufacturing Economic Analysis Summary (part 2)

			Part Name:		
Cost Element	Symbol	Unit	Gripper Fingers	Wrist Motor Shaft	Motor Adaptor
Total Unit Cost (USD)			2.61	5.72	5.97
Qb Units Produced to Break Even			164.28	28728.89	22905.73

Table 6: Redesign Mfg. Process Comparison Summary Milling(right) vs Investment Casting (left)

			Part Name:	
Cost Element	Symbol	Unit	Wrist Joint (Investment Cast)	Wrist Joint (milling)
Total Unit Cost (USD)			8.16	11.36
Qb Units Produced to Break Even			8181.41	1261.48

In the table above we can see a comparison between CNC milling and investment casting. We can see for the milling most of the increased cost comes from increased material requirements and the increased labor time per part. More starting material is needed for the milling since material must be cut away. However, the resale of those waste materials was not considered.

Purchased and Custom Parts

Many the components in the robotic arm are purchased off the shelf. The difference in required purchased components is outlined below. The total cost of all custom components and purchased components is also considered.

Table 7: Original Design All Part Cost Economic Summary

Original Design Off the Shelf Parts			
Purchased Parts Total Cost per Unit			708.88
Original Design Custom Parts			
Custom Parts Total Cost per Unit			76.09
		Unit Price	784.97

Table 8: Redesign All Part Cost Economic Summary

Re-Design Off the Shelf Parts			
Purchased Parts Total Cost per Unit			485.77
Re-Design Custom Parts			
Custom Parts Total Cost per Unit			82.45
		Unit Price	568.22

If we compare the two tables above for the redesign and original design summary where the original design used reductive manufacturing processes to cut material out of aluminum plate to fabricate parts, we can see that the custom unique part count and cost are similar. However, the updated custom parts allow us to eliminate many expensive purchased parts which lead to a reduction in calculated cost of $216.75 or about 28%.

Discussion of Professional, Ethical, and Safety Issues

Being that this is an electromechanical assembly, there will be wiring and high voltage in place for the stepper motors and air regulator attachments. To have a careful understanding of the safety measures in place, our team has assembled this listing to make sure the technicians working on this assembly know the concerns prior to assembly.

Stepper Motors

When any motor is implemented into a system, the voltage and weight must be consistent for a measure of safety. The location of our stepper motors is fastened in a position to consider the wiring that will have to be positioned. Instead of directly driven stepper motors, there are belt and gear attachments. The belts along these voltages to be insulated for the assembly's connecting gears.

These stepper motors can be up to five pounds of weight, which allows for a large moment of inertia when positioned improperly. To account for the large displacement of inertia, our team had redesigned the linkage assembly to have pocket fittings for our components. The pocket feature for these stepper motors is along the centerline of the linkage assembly, therefore is along the centroid axis to eliminate the concern for the assembly to rotate onto its side when in operation.

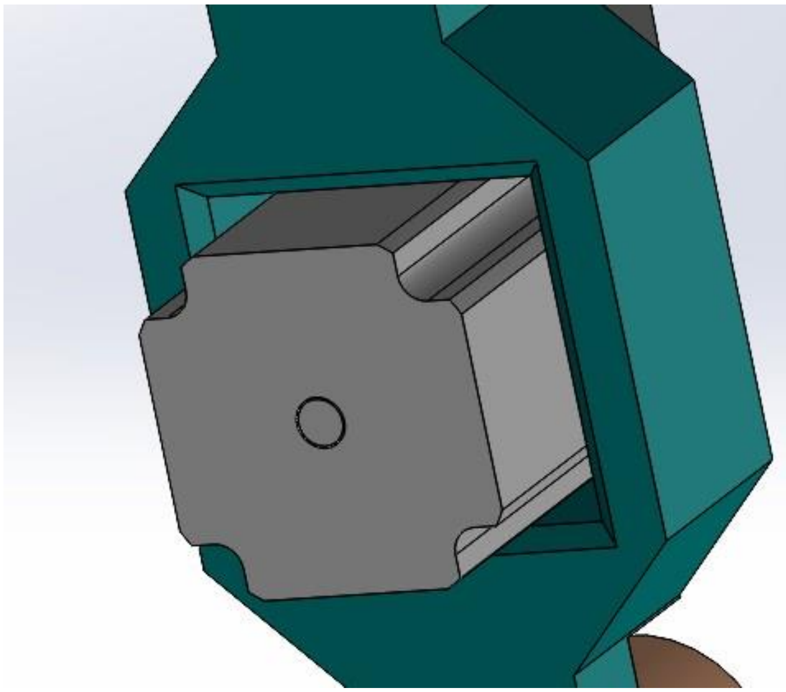


Figure 35: Create Pocketed Stepper Motor

Air Regulator

Beneath the soft robotic gripper is an air regulator to actuate the soft robotic fingers of the assembly. Attached to this regulator are tubes for air flow. There is a concern of the tubes getting tangled along the gripper in reaching a constrained flow, then at maximum pressure to burn out the regulator. To prevent damage to the gripper assembly's air regulator, the component will be fastened in place to the mounting plate of the gripper. When the tubes will be fixed in place, this eliminates the safety concern of a burned-out regulator or any burst in the tubing.

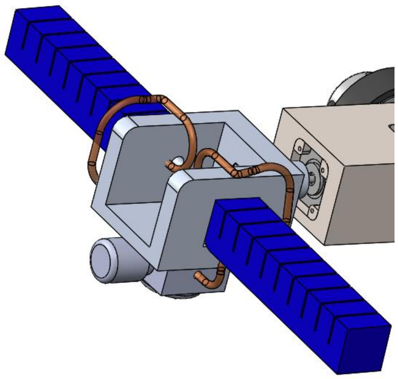


Figure 36: Pneumatic Tubing on Redesign

Selection of Rubber Belts over Bicycle Chains

In selecting the drive systems for the actuating elements, a couple of ideas had been inspired. A range from direct driven design to modified bicycle chains have been discussed. The decision for the bicycle chain would've allowed for a robust design. The component decision of bicycle chains would require sprockets to be in place. In the application of mass production, our team's technicians would constantly have to work with sharp metal components. The selection of rubber adds a metric of safety and decreased measure of secondary operation to our DFA study.

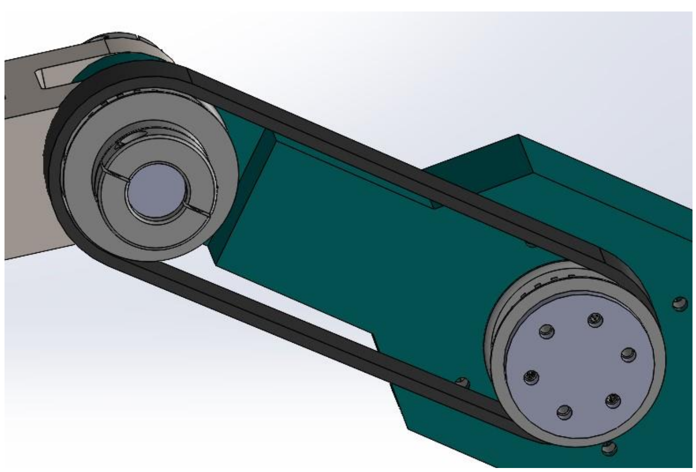


Figure 37: Rubber Belt on Redesign

Discussion of the Redesign

The goal of this redesign was to reduce part count, improve ease of assembly and re-consider material selection which is discussed above. Many components, even purchased components, were merged with custom parts. Reducing part count makes assembly easier. There were a couple of parts that the team wanted to eliminate due to the complexity of their assembly.

Linkage Arm

Two of the pulley gears were integrated into the cast arms to eliminate the screws it would have taken to connect them to the arm and reduce the manufacturing time that it would have taken to remove the plaster from the internal screw hole features. It also eliminated the need to assemble three nuts, three screws, a pulley, and an arm into one assembly. The redesign also integrated previously absent stepper motor mounts into self-locating pockets. It is apparent that the new arm is easier to assemble since each link is composed of just one arm, not two which would need to be aligned and threaded onto multiple shafts. Pockets for bearings to be press-fit into were also added which were absent from the original design. The merged pulley can just be seen at the bottom right of the right image in green.

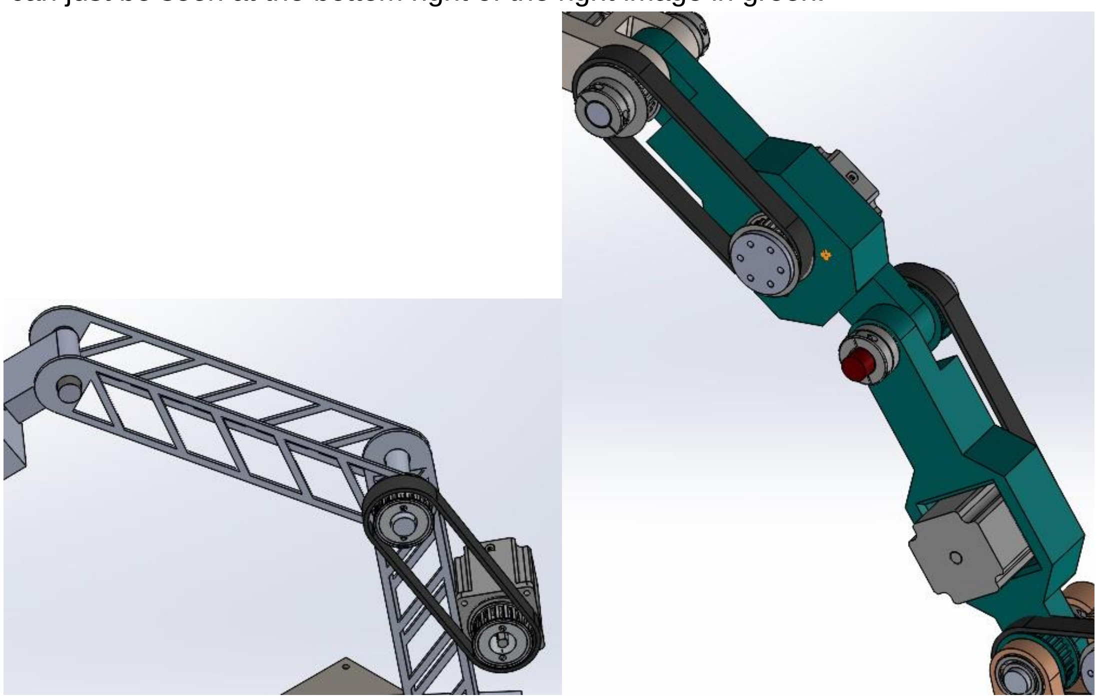
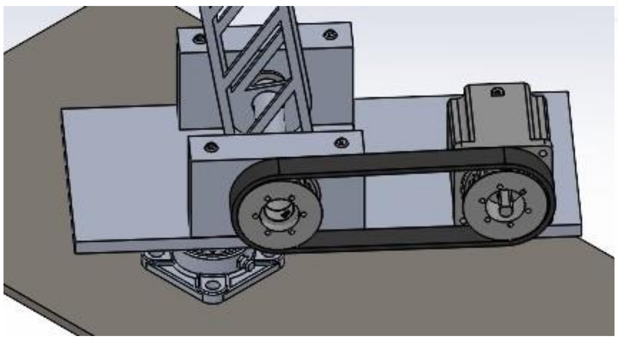


Figure 38: Old Linkage Arm (left) New linkage arm (right)

Shoulder Mount

The shoulder mount part integrated the screws and pillow blocks of the original design by simply adding pockets for bearings to be press fit into. Again, this was done to eliminate parts, and reduce assembly complexity. A self-locating feature in the form of a diagonal brace was also added to make it easier to locate the stepper motor into the assembly. A small pocket in the base of the plate is present to reduce the material required to fabricate the part while a protruded rim remains to offer stiffness. Enough room between the bearing mounts to fit the pulley which is now part of the arm, the arm, and a collar was allowed for. This eliminated the need for a second collar as originally this assembly required two collars. Unfortunately, this assembly still requires screws to mount the motor to it and there is still room for improvement.



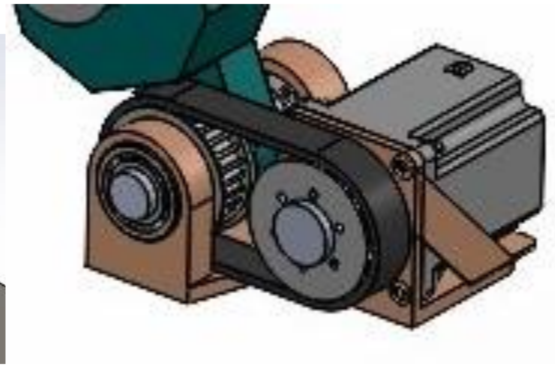
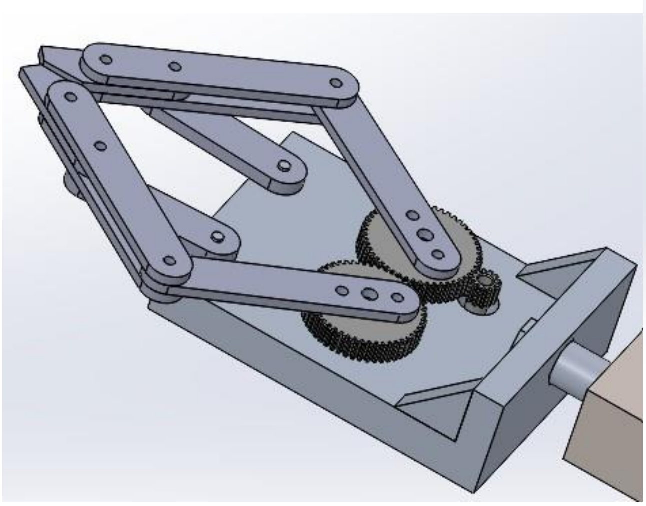


Figure 39: Old Shoulder Plate (left) New Shoulder Plate (right)

Gripper

The gripper underwent a radical redesign. We replaced the rigid linkage-based gripper and gear system with a soft flexible TPU gripper and pneumatic actuation system. This eliminated many parts which made assembly much easier and reduced the cost as the new material was both more affordable and eliminated a large number of expensive purchased components.



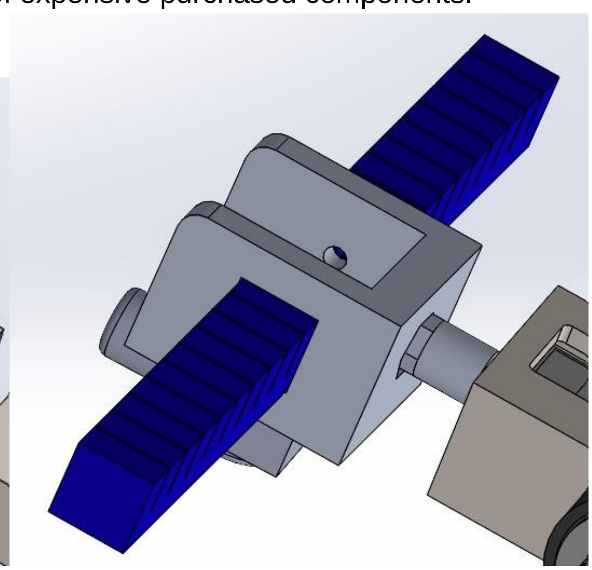


Figure 40: Mechanical Gripper (left) Flexible Gripper (right)

Conclusion

Multiple improvements have been advanced since the evaluation of manufacturability has begun. The original idea would have not been able to support the 5kg masses that would have been required to deliver in the University Rover Challenge. A range of design improvements from the gripper, linkages, and base assembly has been revised for ease of manufacturing. These improvements have allowed for a major decrease in part count, cost, and DFA complexity.

The part count of assembly had an overall decrease of 65 to 53 parts. This part count decrease had resulted in a lower DFA complexity metric to go from 80.22 to 75.31. An initial objective for our team had been to decrease the overall complexity and part count to result in a simplified assembly of a robotic arm. A decrease of 4.97 in complexity number allows our team to know that this is a simplified assembly for this group's hired technician in the case of mass production to 100,000 units.

Soon, there can be a case where these robotic arms will be mass produced and sold to the public, where our team completed an economic analysis of this product when sold at a quantity of 100,000 units. From the original design, there had been a unit price of $784.97. After complete redesigns, the new assembly had been listed at a final unit price of $568.22. Through this study, our team had increased the affordability of this assembly by $216.75.

The study of manufacturability for this robotic arm has decreased complexity and increased cost-effectiveness for our users. In doing so, our team believes that one day it would be affordable for people and companies to be interested in purchasing our cost-effective assembly for a wide range of practical uses in the robotic industry.

References

Charbel Tawk, Geoffrey M Spinks, Gursel Alici, “3D Printable Linear Soft Vacuum Actuators: Their Modeling, Performance Quantification and Application in Soft Robotic Systems”, https://ieeexplore.ieee.org/document/8788588

Chenyu Zheng, “Design and simulation of a pneumatic actuator bending soft robotics based on 3D printing”, https://mds.marshall.edu/cgi/viewcontent.cgi?article=2251&context=etd

Peter Heinrich Stephen, Josh Person, Brad Wood, “US Patent 6,345,818 B1”, https://pdfpiw.uspto.gov/.piw?docid=06345818

Guy W.Rhodes, John W.Hill, Clement M.Smith “US Patent 4,806,066”, https://patents.google.com/patent/US4806066A/en

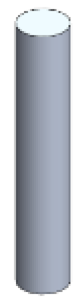
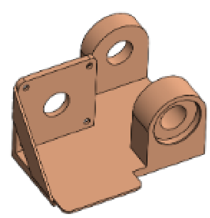
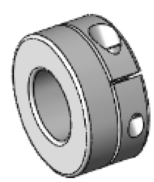
Material property charts, https://www.grantadesign.com/education/students/charts/

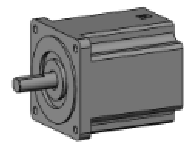
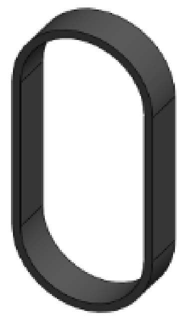
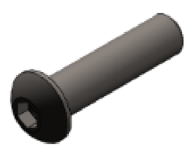
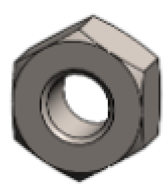
ABAQUS tutorial video, https://www.youtube.com/watch?v=hwhjfwHjYnQ&t=617s

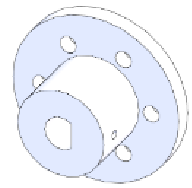
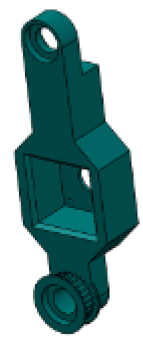
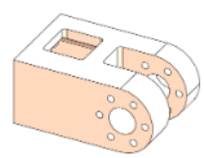
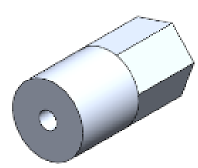
ABAQUS User Manual Guide, http://130.149.89.49:2080/v6.14/books/usb/default.htm

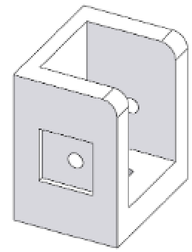
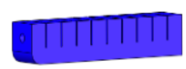
Appendix

Redesign Bill of Materials (BOM)

Part Number	Name	Quantity	Part in Assembly	Subassembly
1.01, 2.08, 3.02	Motion Adapter Shaft OD 1"	3		Base, Linkage, Wrist
1.02	Shoulder Mount	1		Base
1.03, 2.03	Shaft Collar ID 1"	5		Base, Linkage
1.04, 2.04	Ball Bearing	9		Base, Linkage

Part Number	Name	Quantity	Part in Assembly	Subassembly
1.05, 2.07, 3.04	DC Control Stepper Motor	3		Base, Linkage, Wrist
1.06	Puley Belt ¼" thick- short	1		Base
2.06	Pulley Belt 1/4" thick- long	2		Linkage
1.07, 3.05	Button Head Cap Screws 1/4"-28 (x inch long) -Motor	8		Base, Wrist
1.08	Hex Nut	4		Base
1.09, 2.05	Pulley Gear (hex bolt Pattern)	3		Base, Linkage

Part Number	Name	Quantity	Part in Assembly	Subassembly
1.1, 2.09	Motor Adapter	3		Base, Linkage
2.01, 2.02	Proximal/Distal Bar Linkage	2		Linkage
3.01	Wrist Joint	1		Wrist
3.03	Wrist Motor Shaft	1		Wrist
4.01	Regulator	1		Gripper

Part Number	Name	Quantity	Part in Assembly	Subassembly
4.02	Finger Mounting Plate	1		Gripper
4.03	Pressure Tubes	1		Gripper
4.04	Gripper Fingers	2		Gripper

Economic Analysis Supporting Material

Economic Analysis of Investment Casting vs Milling for a 100,000 Unit Production Volume

			Part Name:	
Cost Element	Symbol	Unit	Mounting Joint (Investment Casting)	Mounting Joint (milling)
Material Cost	cm	USD/lb	1.48	1.48
Material Waste Fraction	f	fraction	0.05	0.5
Mass of part	m	lb	2.0	2
Cm Unit Cost of Material	**Cm**	USD	3.09	5.92
Labor Cost	cw	USD/hr	25	25
Production Rate	n dot	unit/hr	10	6
CL Unit Cost of Labor	**CL**	USD	2.50	4.17
Tooling cost	ct	USD/set	218000	55000
Tool Production Run	n	units	100000	100000
Tooling Life	nt	units	300000	200000
Number of Machines	nm		1	1
Sets of Tooling Required	k	sets	1	1
Unit Cost of Tooling	**CT**	USD	2.18	0.55
Capital Equipment Cost (all)	ce	USD	20000	10000
Capital Write Off Time	two	yrs	5	5
Hours/ yr Equipment is Operated	Hyr	hr/yr	2000	2000
Load Fraction	L	fraction	1	1
Load Sharing Fraction	q	fraction	0.250	1.000
Unit Cost of Capital Equipment	**Ce**	USD	0.05	0.17
Factory Overhead	cOH	USD/hr	3.33	3.33
Production Rate	n dot	unit/hr	10	6
Unit Cost of Factory Overhead	**COH**	USD	0.33	0.56
Total Unit Cost (USD)			8.16	11.36
Qb Units Produced to Break Even			8181.41	1261.48
1:3:9 Sanity Check	**Material**	**1**	3.09	5.92
	Mfg.	**3**	9.28	17.76
	Price	**9**	27.85	53.28

Economic Analysis of Redesign (part 1)

			Part Name:			
Cost Element	Symbol	Unit	Shoulder Mounting Plate	Bar Linkage	Wrist Joint	Shoulder Mount
Material Cost	cm	USD/lb	1.48	1.48	1.48	1.48
Material Waste Fraction	f	fraction	0.05	0.05	0.05	0.08
Mass of part	m	lb	1.56	6.4	2.0	1.84
Cm Unit Cost of Material	**Cm**	USD	2.44	9.97	3.09	2.96
Labor Cost	cw	USD/hr	25	25	25	25
Production Rate	n dot	unit/hr	10	10	10	10
CL Unit Cost of Labor	**CL**	USD	2.50	2.50	2.50	2.50
Tooling cost	ct	USD/set	218000	218000	218000	218000
Tool Production Run	n	units	100000	100000	100000	100000
Tooling Life	nt	units	300000	300000	300000	300000
Number of Machines	nm		1	1	1	1
Sets of Tooling Required	k	sets	1	1	1	1
Unit Cost of Tooling	**CT**	USD	2.18	2.18	2.18	2.18
Capital Equipment Cost (all)	ce	USD	20000	20000	20000	20000
Capital Write Off Time	two	yrs	5	5	5	5
Hours/ yr Equipment is Operated	Hyr	hr/yr	2000	2000	2000	2000
Load Fraction	L	fraction	1	1	1	1
Load Sharing Fraction	q	fraction	0.250	0.250	0.250	0.250
Unit Cost of Capital Equipment	**Ce**	USD	0.05	0.05	0.05	0.05
Factory Overhead	cOH	USD/hr	3.33	3.33	3.33	2
Production Rate	n dot	unit/hr	10	10	10	10
Unit Cost of Factory Overhead	**COH**	USD	0.33	0.33	0.33	0.20
Total Unit Cost (USD)			7.50	15.03	8.16	7.89
Qb Units Produced to Break Even			10136.66	2710.78	8181.41	8517.32
1:3:9 Sanity Check	**Material**	**1**	2.44	9.97	3.09	2.96
	Mfg.	**3**	7.31	29.91	9.28	8.88
	Price	**9**	21.94	89.73	27.85	26.64

Economic Analysis of Redesign (part 2)

			Part Name:		
Cost Element	Symbol	Unit	Gripper Fingers	Wrist Motor Shaft	Motor Adaptor
Material Cost	cm	USD/lb	1.36	1.48	1.48
Material Waste Fraction	f	fraction	0.05	0.1	0.1
Mass of part	m	lb	0.48	0.40	0.55
Cm Unit Cost of Material	**Cm**	USD	0.69	0.66	0.90
Labor Cost	cw	USD/hr	15	25	25
Production Rate	n dot	unit/hr	10	10	10
CL Unit Cost of Labor	**CL**	USD	1.50	2.50	2.50
Tooling cost	ct	USD/set	150	218000	218000
Tool Production Run	n	units	100000	100000	100000
Tooling Life	nt	units	100000	300000	300000
Number of Machines	nm		50	1	1
Sets of Tooling Required	k	sets	1	1	1
Unit Cost of Tooling	**CT**	USD	0.08	2.18	2.18
Capital Equipment Cost (all)	ce	USD	1000	20000	20000
Capital Write Off Time	two	yrs	5	5	5
Hours/ yr Equipment is Operated	Hyr	hr/yr	2000	2000	2000
Load Fraction	L	fraction	1	1	1
Load Sharing Fraction	q	fraction	1.000	0.250	0.250
Unit Cost of Capital Equipment	**Ce**	USD	0.01	0.05	0.05
Factory Overhead	cOH	USD/hr	3.33	3.33	3.33
Production Rate	n dot	unit/hr	10	10	10
Unit Cost of Factory Overhead	**COH**	USD	0.33	0.33	0.33
Total Unit Cost (USD)			2.61	5.72	5.97
Qb Units Produced to Break Even			164.28	28728.89	22905.73
1:3:9 Sanity Check	**Material**	**1**	0.69	0.66	0.90
	Mfg.	**3**	2.06	1.97	2.71
	Price	**9**	6.19	5.92	8.14

Economic Analysis of Original Design (part 1)

			Part Name:			
Cost Element	Symbol	Unit	Mounting Plate	Bar Linkages (Plate)	Wrist Joint	Proximal Finger
Material Cost	cm	USD/lb	1.48	1.48	1.48	1.48
Material Waste Fraction	f	fraction	0.05	0.05	0.05	0.05
Mass of part	m	lb	3.20	3.1	2.2	0.28
Cm Unit Cost of Material	**Cm**	USD	4.99	4.83	3.43	0.44
Labor Cost	cw	USD/hr	25	25	25	25
Production Rate	n dot	unit/hr	10	10	10	30
CL Unit Cost of Labor	**CL**	USD	2.50	2.50	2.50	0.83
Tooling cost	ct	USD/set	10000	130000	218000	19520
Tool Production Run	n	units	100000	100000	100000	100000
Tooling Life	nt	units	50000	50000	300000	50000
Number of Machines	nm		1	1	1	1
Sets of Tooling Required	k	sets	2	2	1	2
Unit Cost of Tooling	**CT**	USD	0.20	2.60	2.18	0.39
Capital Equipment Cost (all)	ce	USD	10000	10000	20000	2000
Capital Write Off Time	two	yrs	5	5	5	5
Hours/ yr Equipment is Operated	Hyr	hr/yr	2000	2000	2000	2000
Load Fraction	L	fraction	1	1	1	1
Load Sharing Fraction	q	fraction	1.000	1.000	1.000	1.000
Unit Cost of Capital Equipment	**Ce**	USD	0.10	0.10	0.20	0.01
Factory Overhead	cOH	USD/hr	3.33	3.33	3.33	3.33
Production Rate	n dot	unit/hr	10	10	10	30
Unit Cost of Factory Overhead	**COH**	USD	0.33	0.33	0.33	0.11
Total Unit Cost (USD)			8.12	10.36	8.64	1.78
Qb Units Produced to Break Even			471.90	3160.39	7954.83	4978.00
1:3:9 Sanity Check	**Material**	**1**	4.99	4.83	3.43	0.44
	Mfg.	**3**	14.96	14.49	10.28	1.31
	Price	**9**	44.87	43.47	30.85	3.93

Economic Analysis of Original Design (part 2)

			Part Name:		
Cost Element	**Symbol**	**Unit**	**Medial Finger**	**Distal Finger**	**Mounting Plate (grippers)**
Material Cost	cm	USD/lb	1.48	1.48	1.48
Material Waste Fraction	f	fraction	0.05	0.05	0.05
Mass of part	m	lb	0.24	0.50	1.20
Cm Unit Cost of Material	**Cm**	USD	0.37	0.78	1.87
Labor Cost	cw	USD/hr	25	25	25
Production Rate	n dot	unit/hr	30	30	30
CL Unit Cost of Labor	**CL**	USD	0.83	0.83	0.83
Tooling cost	ct	USD/set	19520	19520	19520
Tool Production Run	n	units	100000	100000	100000
Tooling Life	nt	units	50000	50000	50000
Number of Machines	nm		1	1	1
Sets of Tooling Required	k	sets	2	2	2
Unit Cost of Tooling	**CT**	USD	0.39	0.39	0.39
Capital Equipment Cost (all)	ce	USD	2000	2000	2000
Capital Write Off Time	two	yrs	5	5	5
Hours/ yr Equipment is Operated	Hyr	hr/yr	2000	2000	2000
Load Fraction	L	fraction	1	1	1
Load Sharing Fraction	q	fraction	1.000	1.000	1.000
Unit Cost of Capital Equipment	**Ce**	USD	0.01	0.01	0.01
Factory Overhead	cOH	USD/hr	3.33	3.33	3.33
Production Rate	n dot	unit/hr	30	30	30
Unit Cost of Factory Overhead	**COH**	USD	0.11	0.11	0.11
Total Unit Cost (USD)			1.72	2.12	3.21
Qb Units Produced to Break Even			5626.89	3046.04	1362.96
1:3:9 Sanity Check	**Material**	**1**	0.37	0.78	1.87
	Mfg.	**3**	1.12	2.34	5.61
	Price	**9**	3.37	7.01	16.83

Total Cost Economic Analysis of Original Design Including Purchased Parts and Considering Unique Part Quantity per Robotic Arm

Original Design Off the Shelf Parts			
Part	Quantity	Price	Total
Belt	3	16.58	49.74
Pully gear	6	13.99	83.94
Stepper motor	3	74.81	224.43
DC motor	1	12.78	12.78
1 inch shaft	5	4.34	21.68
Collar	12	2.93	35.16
Ball Bearing	12	8.02	96.24
1/4 in Screw	25	0.33	8.33
1/4 in Nut	25	0.32	8.00
Pressure Reg.	1	22.5	22.50
Pillow Block	2	13	26.00
Planar gear	4	30.02	120.08
Purchased Parts Total Cost per Unit			708.88
Original Design Custom Parts			
Part	Quantity	Price	Total
Mounting Plate	1	8.12	8.12
Bar Linkages (Plate)	4	10.36	41.44
Wrist Joint	1	8.64	8.64
Proximal Finger	2	1.78	3.56
Medial Finger	4	1.72	6.88
Distal Finger	2	2.12	4.24
Mounting Plate (Grippers)	1	3.21	3.21
Custom Parts Total Cost per Unit			76.09
		Unit Price	784.97

Total Cost Economic Analysis of Redesign Including Purchased Parts and Considering Unique Part Quantity per Robotic Arm

Re-Design Off the Shelf Parts			
Part	Quantity	Unit Price	Total Price
Belt	3	16.58	49.74
Pully gear	3	13.99	41.97
Stepper motor	3	74.46	223.37
DC motor	1	12.78	12.78
1 inch shaft	3	4.34	13.01
Collar	5	2.93	14.65
Ball Bearing	12	8.02	96.24
1/4 in Screw	16	0.33	5.33
1/4 in Nut	16	0.32	5.12
Pressure Tubing (1ft.)	2	0.53	1.06
Pressure Reg.	1	22.5	22.50
Purchased Parts Total Cost per Unit			485.77
Re-Design Custom Parts			
Part	Quantity	Unit Price	Total Price
Shoulder Mounting Plate	1	7.50	7.50
Bar Linkage	2	15.03	30.07
Wrist Joint	1	8.16	8.16
Shoulder Mount	1	7.89	7.89
Gripper Fingers	2	2.61	5.21
Wrist Motor Shaft	1	5.72	5.72
Motor Adaptor	3	5.97	17.90
Custom Parts Total Cost per Unit			82.45
		Unit Price	568.22

Assembly Drawings of Product

Attached are the assembly drawings of the product listed in the table below in the following order. All drawings have been updated including dimensions and GD&T.

Drawings by Subassembly

Drawing Assembly	Revision
Arm	B
Base	B
Bar Linkage	B
Wrist	B
Gripper	B

Dimensioned Orthographic Drawings for Custom Parts

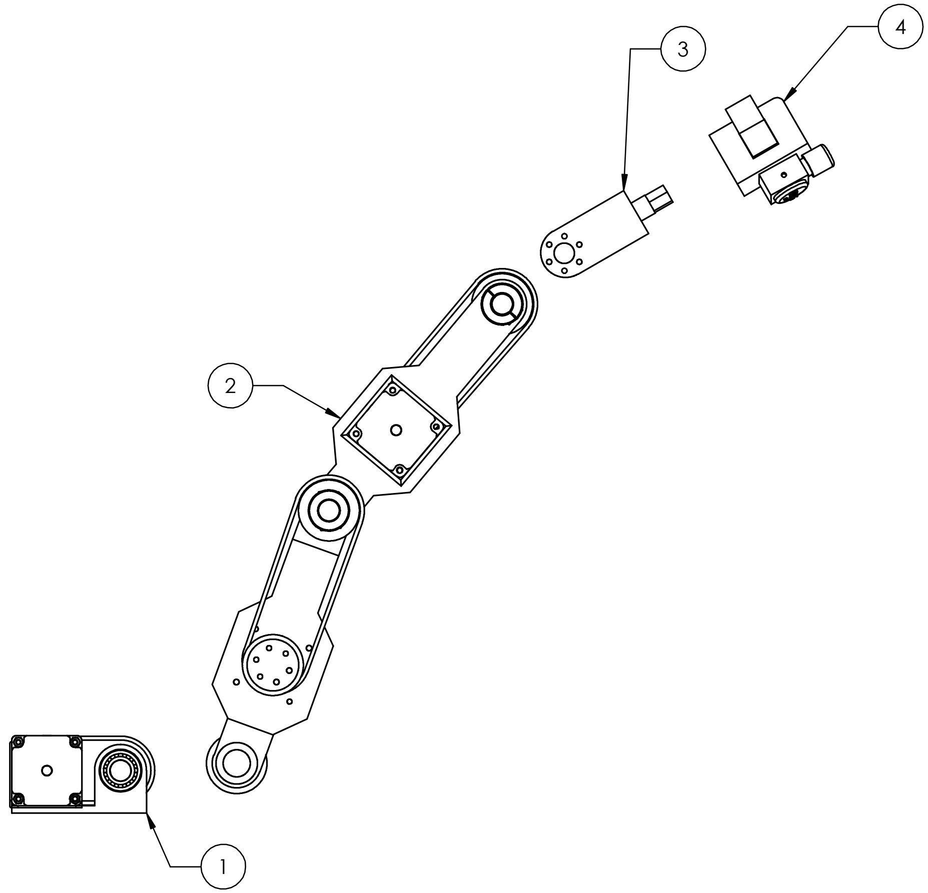
The custom parts each have dimensioned orthographic drawings. The table below is a list of the drawings in order. Each drawing is updated with proper dimensions and GD&T.

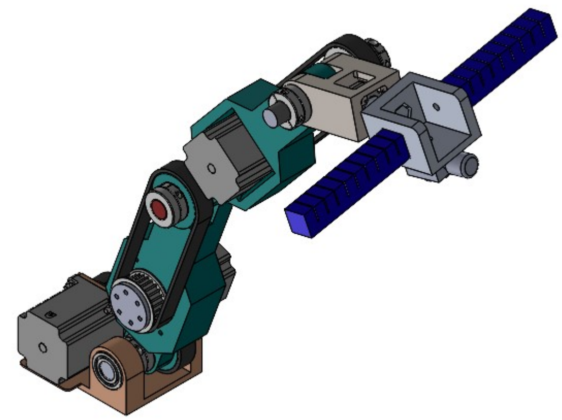
Redesign: Custom Drawing List

Drawing Component	Revision
Motor Adapter	B
Bar Linkage	B
Wrist Joint	B
Wrist Motor Shaft	B
Mounting Plate for Gripper	B
Gripper	B

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	04/15/2022
B	CHANGE TO SUBASSEMBLIES	04/18/2022

ITEM NO.	QTY.	PART NUMBER
1	1	BASE ASSEMBLY
2	1	BAR LINKAGE ASSEMBLY
3	1	WRIST ASSEMBLY
4	1	GRIPPER ASSEMBLY





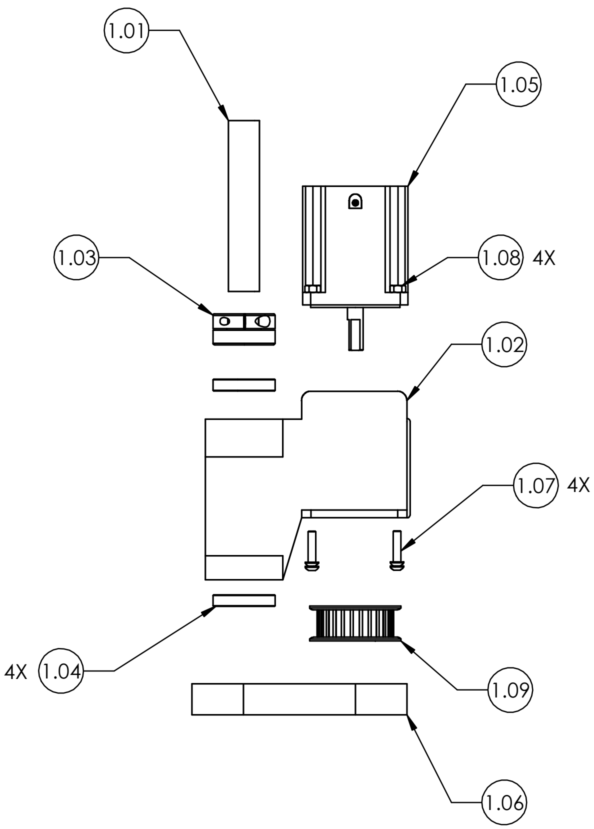
ISOMETRIC VIEW

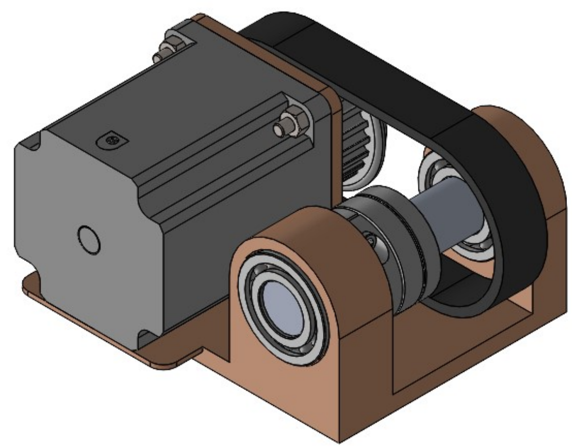
MARS ROVER'S ROBOTIC ARM
UNIVERSITY OF COLORADO
MCEN 5045

DRAWN BY	DESCRIPTION				
MICHAEL DECAPUA	ARM ASSEMBLY				
CHECKED BY	PN -	REV A		SHEET 1 of 5	

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	04/15/2022
B	SHORTEN BELT CONFIGURATION	04/18/2022

ITEM NO.	QTY.	PART NUMBER
1.01	1	SHOULDER MOTOR ADAPTER SHAFT OD 1"
1.02	1	SHOULDER MOUNT
1.03	1	SHAFT COLLAR ID 1"
1.04	4	BALL BEARING
1.05	1	DC CONTROL STEPPER MOTOR
1.06	1	PULLEY BELT 1/4" THICK
1.07	4	BUTTON HEAD CAP SCREWS 1/4"-28
1.08	4	HEX NUT
1.09	1	PULLEY GEAR
1.10	1	PULLEY GEAR WRIST MOTOR ADAPTER





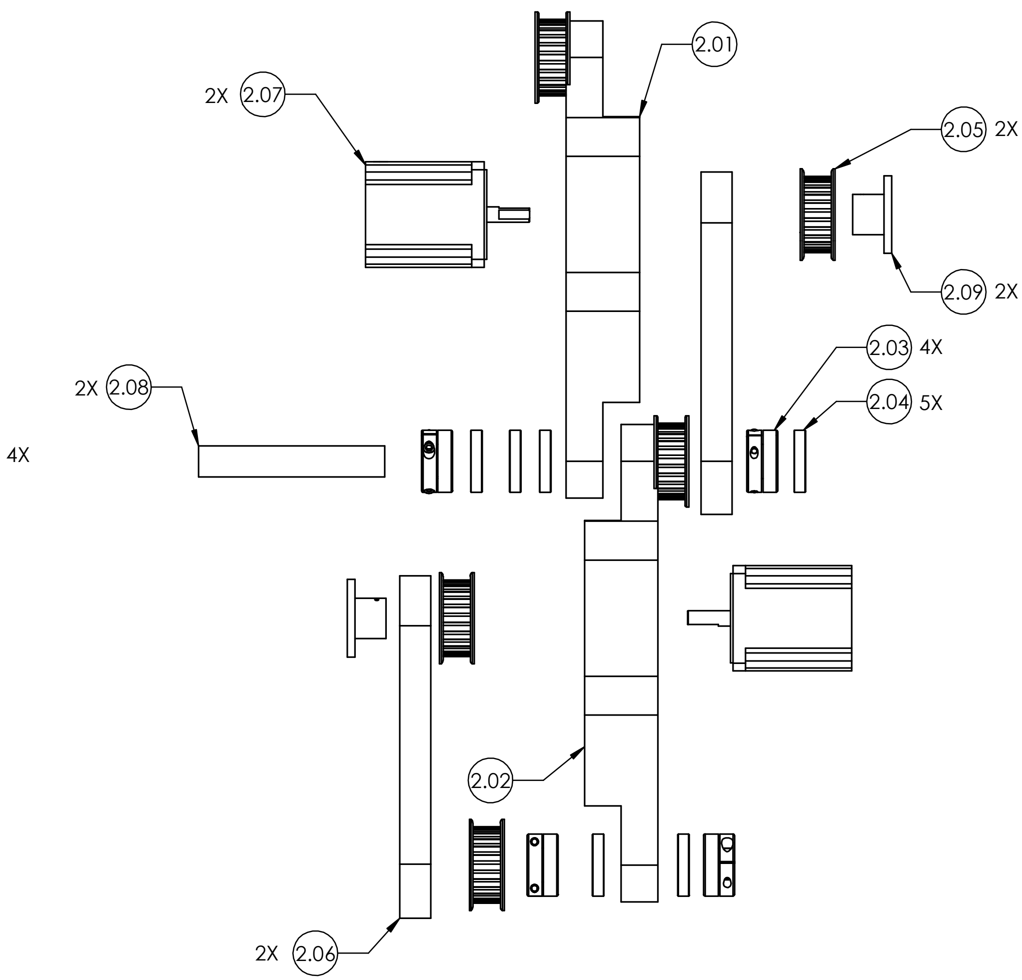
ISOMETRIC VIEW

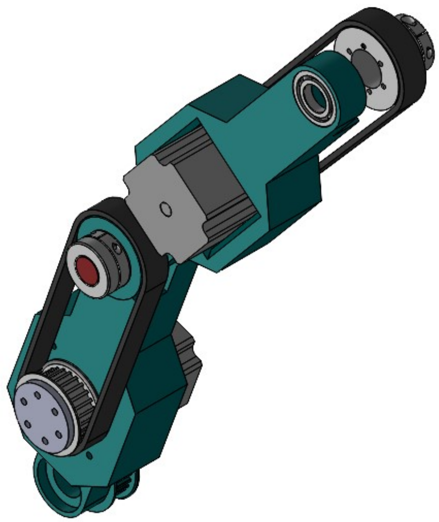
MARS ROVER'S ROBOTIC ARM
UNIVERSITY OF COLORADO
MCEN 5045

DRAWN BY MICHAEL DECAPUA	DESCRIPTION BASE ASSEMBLY			
CHECKED BY	PN -	REV A		SHEET 2 of 5

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	04/15/2022
B	THICKNESS CHANGE	04/18/2022

ITEM NO.	QTY.	PART NUMBER
2.01	1	PROXIMAL BAR LINKAGE
2.02	1	DISTAL BAR LINKAGE
2.03	4	SHAFT COLLAR ID 1"
2.04	5	BALL BEARING
2.05	2	PULLEY GEAR (HEX BOLT PATTERN)
2.06	2	PULLEY BELT
2.07	2	DC CONTROL STEPPER MOTOR
2.08	2	ELBOW MOTION ADAPTER SHAFT OD 1"
2.09	2	ELBOW MOTOR ADAPTER





ISOMETRIC VIEW

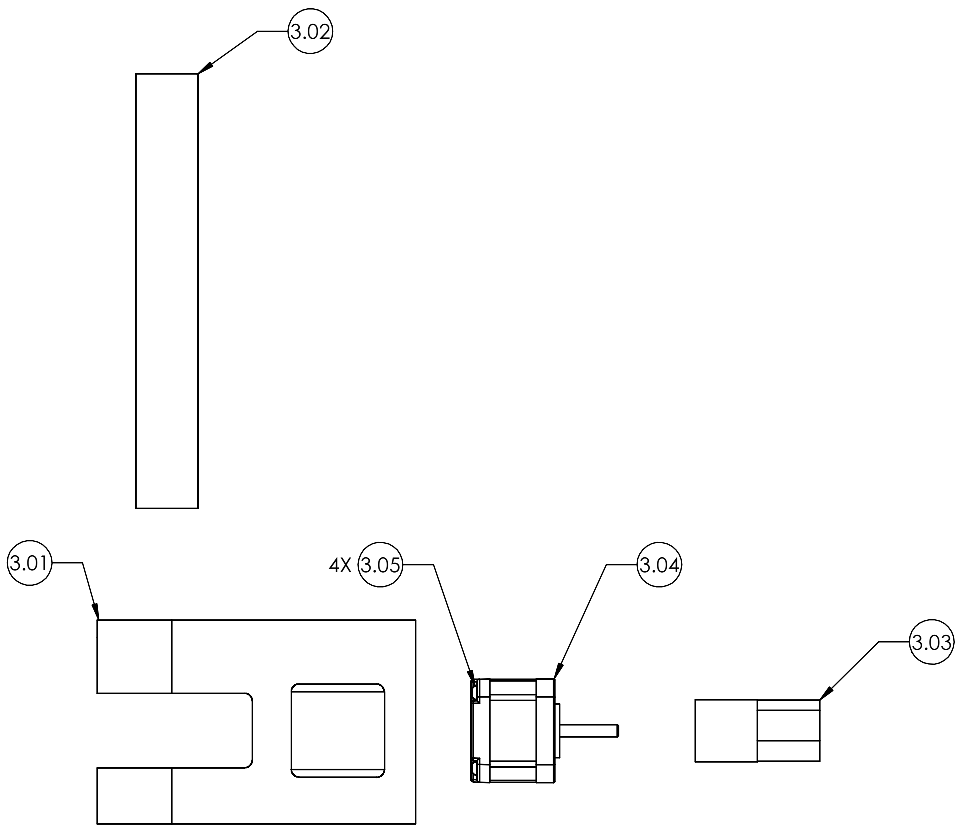
MARS ROVER'S ROBOTIC ARM
UNIVERSITY OF COLORADO
MCEN 5045

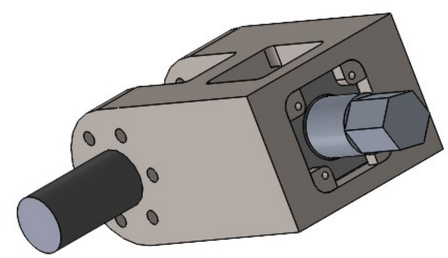
DRAWN BY	DESCRIPTION			SHEET
MICHAEL DECAPUA	BAR LINKAGE ASSEMBLY			
CHECKED BY	PN	REV		SHEET
	-	A		3 of 5

PROPRIETARY AND CONFIDENTIAL THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF . ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT WRITTEN PERMISSION IS PROHIBITED.

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	04/15/2022
B	INCLUDES TOP POCKET	04/18/2022

ITEM NO.	QTY.	PART NUMBER
3.01	1	WRIST JOINT
3.02	1	WRIST SHAFT ADAPTER OD 1"
3.03	1	WRIST MOTOR SHAFT
3.04	1	DC CONTROL STEPPER MOTOR
3.05	4	MOTOR MOUNT SCREWS





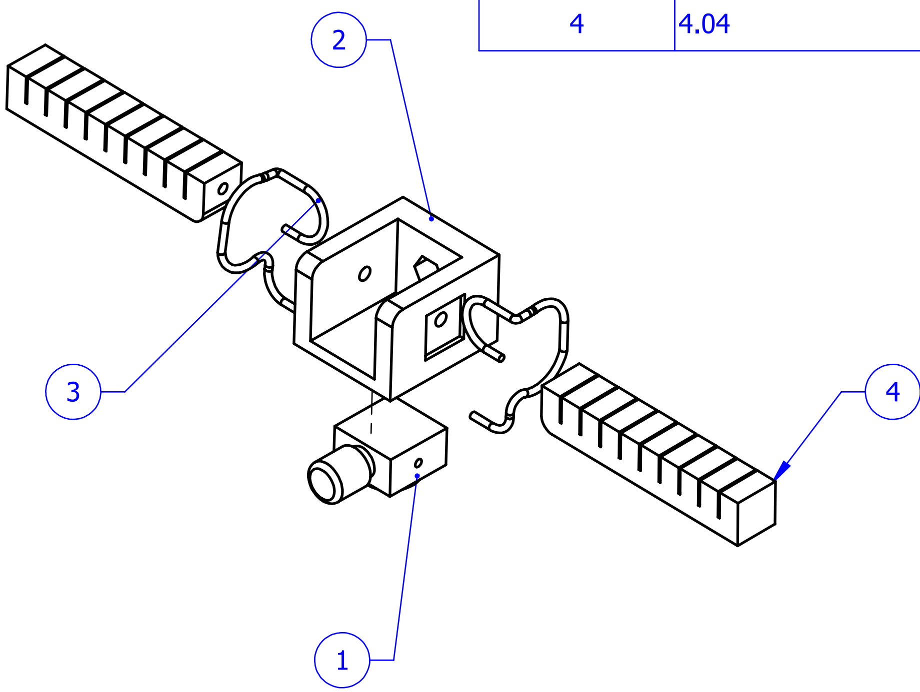
ISOMETRIC VIEW

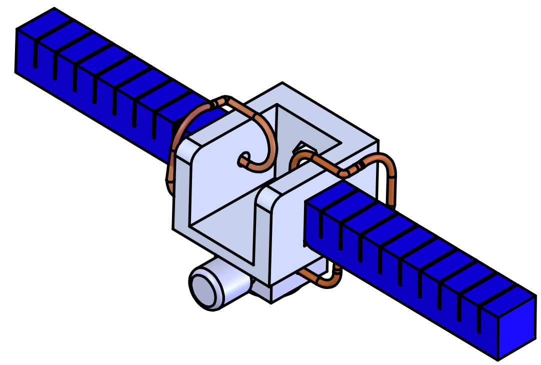
MARS ROVER'S ROBOTIC ARM
UNIVERSITY OF COLORADO
MCEN 5045

DRAWN BY MICHAEL DECAPUA	DESCRIPTION WRIST ASSEMBLY
CHECKED BY	PN - / REV A / SHEET 4 of 5

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	15-04-2022
B	SOFT GRIPPER MODULE HAS BEEN IMPLEMENTED	19-04-2022

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	4.01	PRESSURE REGULATOR	1
2	4.02	MOUNTING PLATE	2
3	4.03	SOFT GRIPPER FINGER	1
4	4.04	PRESSURE TUBE	2





ISOMETRIC VIEW

NOTES:

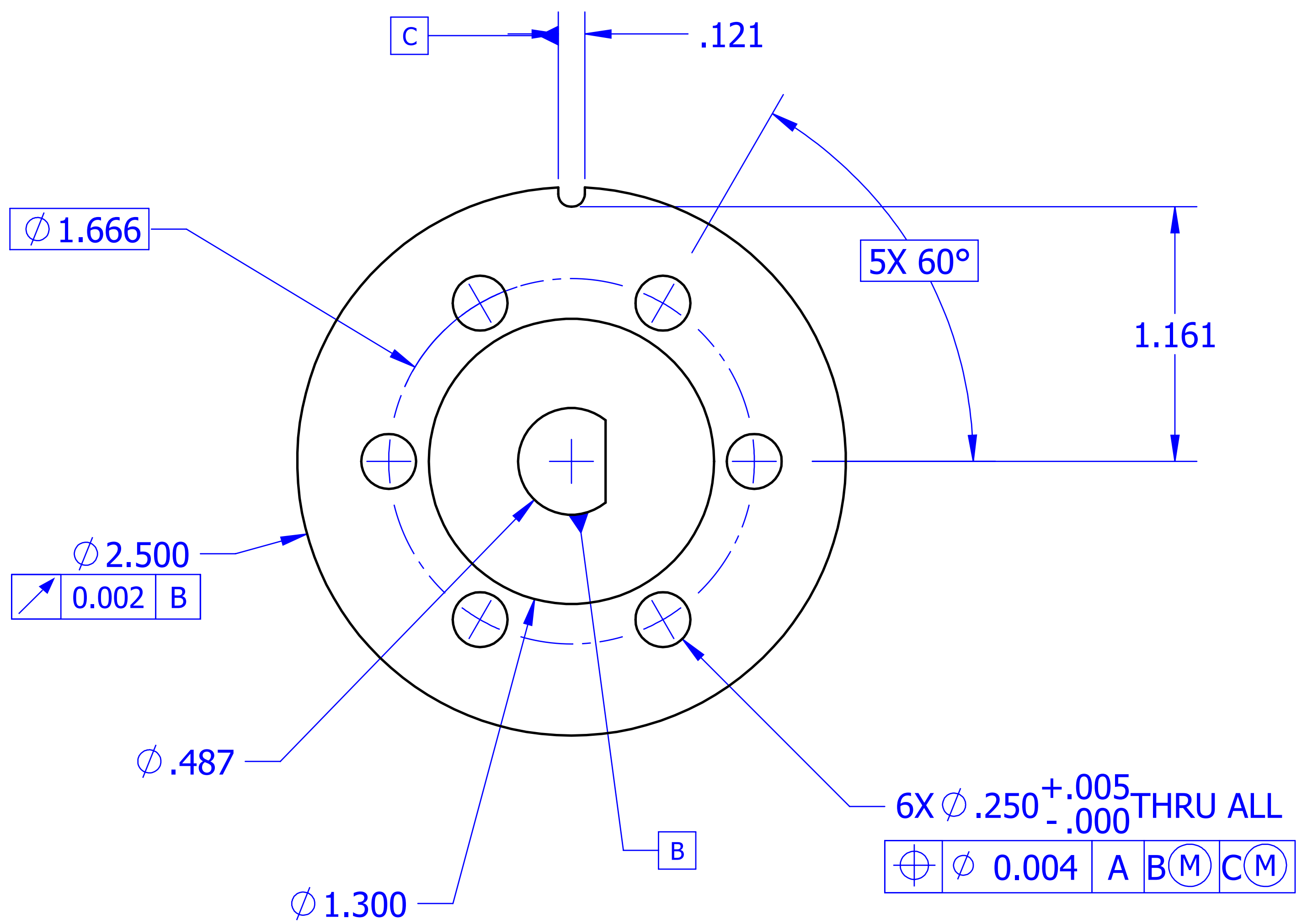
1. ITEM 3 IS PLACED ONTO THE BASE OF ITEM 1 USING AHDESIVES
2. ITEM 2 IS CONNECTED WITH ITEM3 USING ITEM 4 (PRESSURE TUBES).

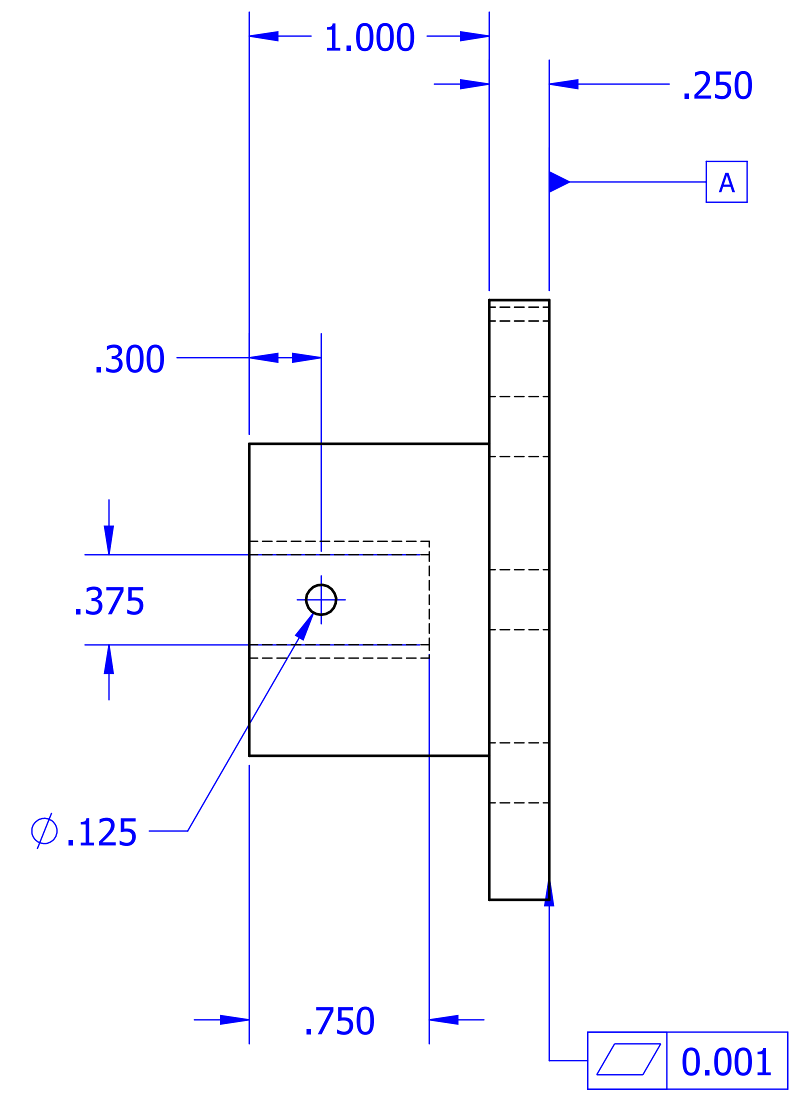
UNIVERSITY OF COLORADO

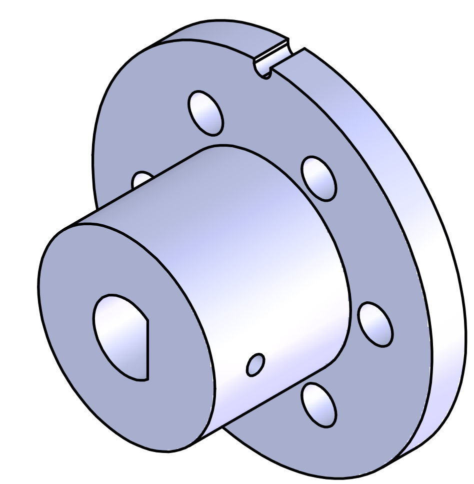
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427

DESCRIPTION			
GRIPPER SUBASSEMBLY			
PN 4	REV B		SHEET 1 of 1

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	17-04-2022
B	FINAL RELEASE- TOLERANCES WERE UPDATED	19-04-2022







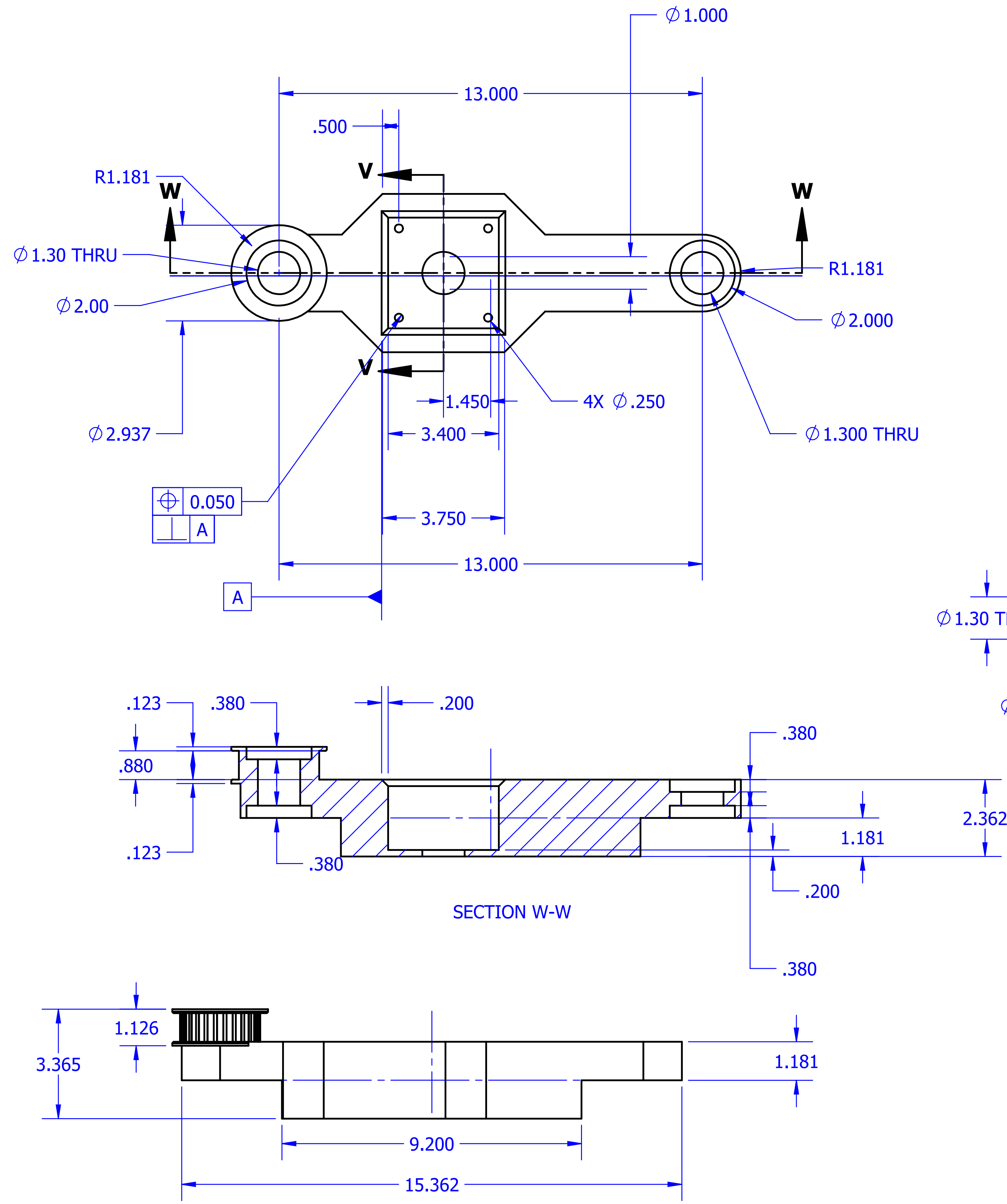
ISOMETRIC VIEW

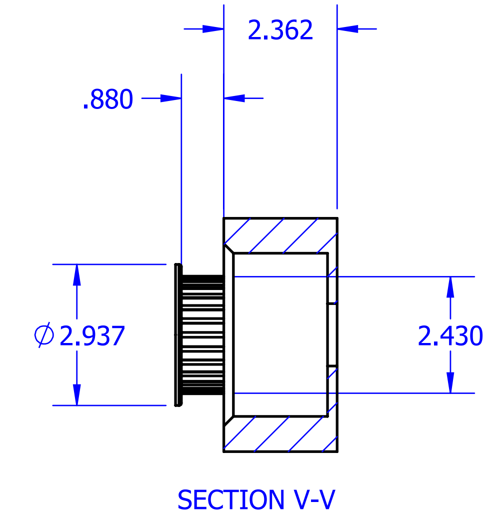
NOTES:
1. DEBURR ALL SHARP EDGES EXCEPT AS NOTED.

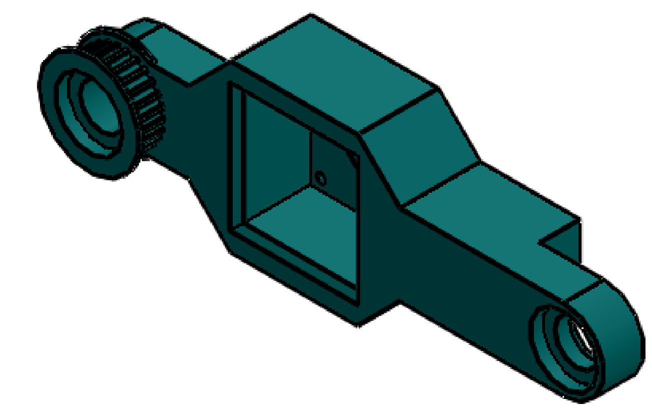
TOLERANCES UNLESS NOTED: X.X ± 0.050, X.XX ±0.010, X.XXX ±0.005, X.X° 1°	UNITS: INCHES	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427
MATERIAL ALUMINUM		DESCRIPTION WRIST MOTOR ADAPTER
FINISH NONE		PN 1.10 · REV B · SHEET 1 of 1

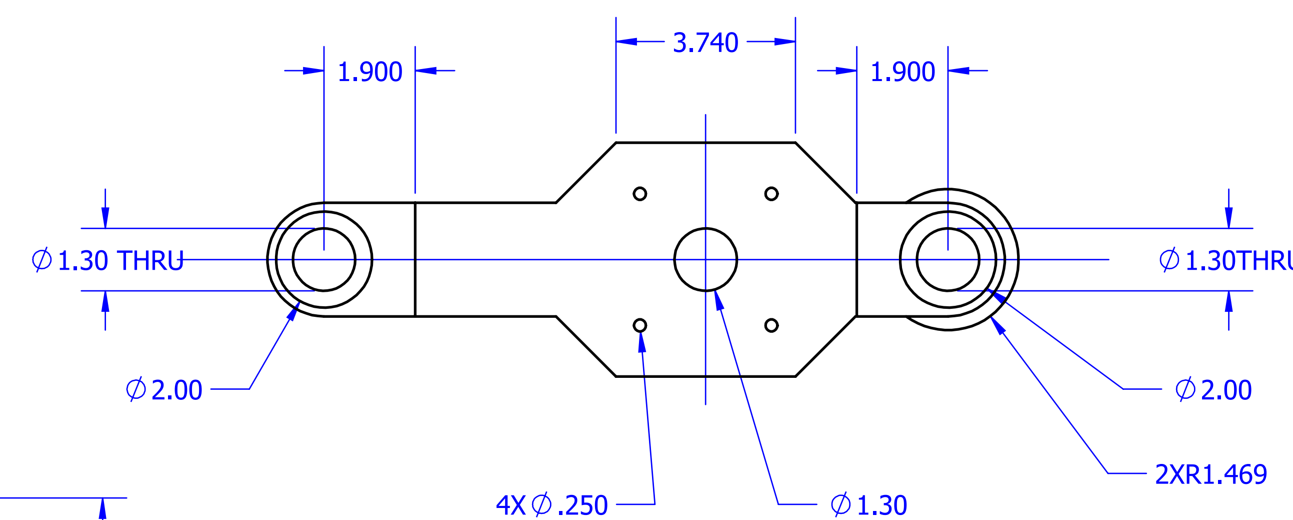
PROPRIETARY AND CONFIDENTIAL

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	4/15/22
B	ADDED POCKET FOR MOTOR AND BEARINGS; ADAPTED CAST FOR PULLEY GEAR DESIGN (SEE NOTE #1)	4/18/2022





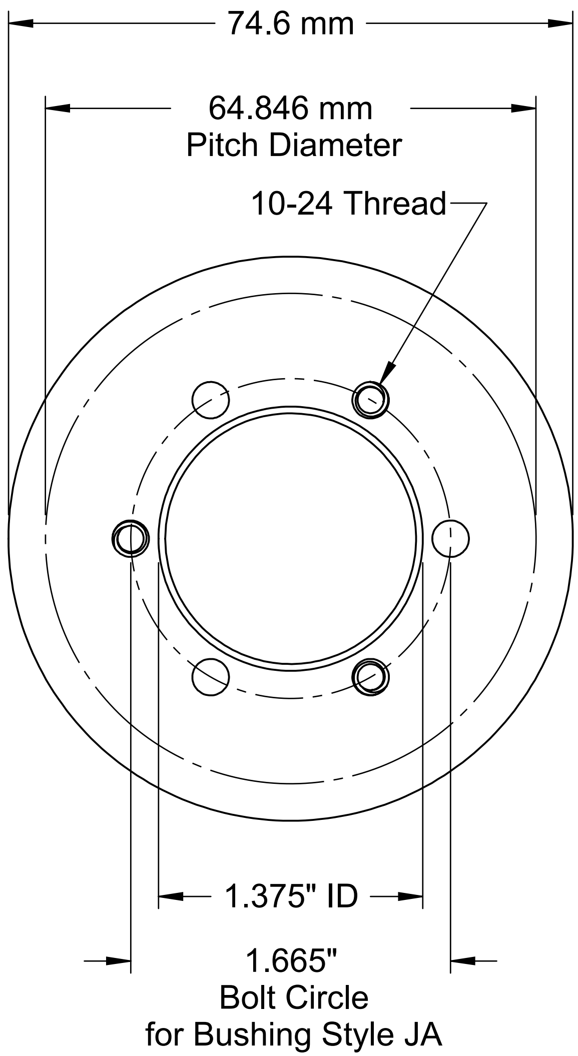


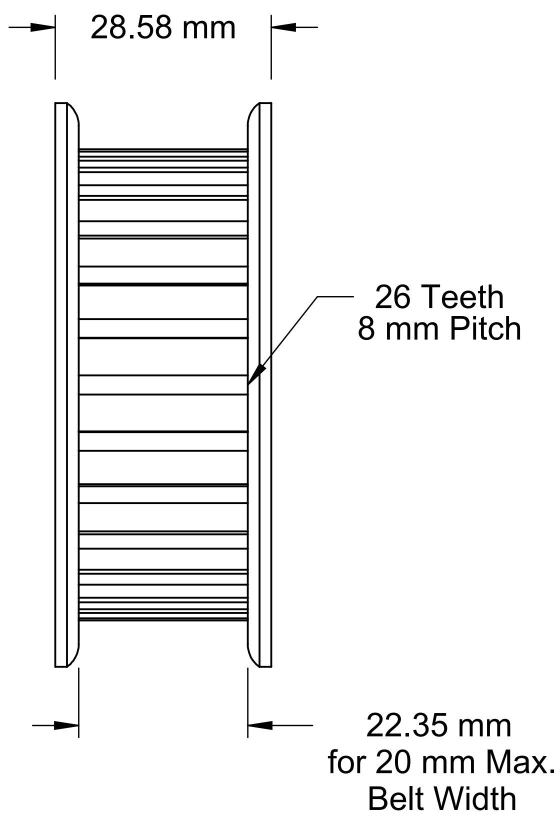


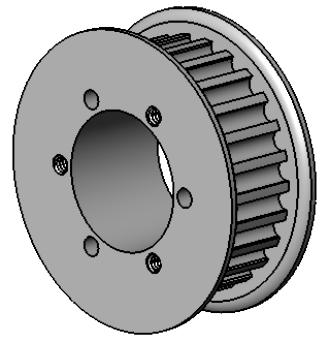
NOTES:

1. FEATURE OF PULLY IS OF 26 TEETH, 8MM PITCH, AND 74.66 MM OD TO INTEGRATE WITH A 20MM WIDE BELT (SEE REFERENCED PART 123N016- MC MASTER CARR DRAWING)

TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005 X.X° 1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427
UNITS: INCHES		
MATERIAL: ALUMINIUM		DESCRIPTION: PROXIMAL/DISTAL BAR LINKAGE
FINISH: NONE		PN: 2.01, 2.02 — REV: B — SHEET: 1 of 1







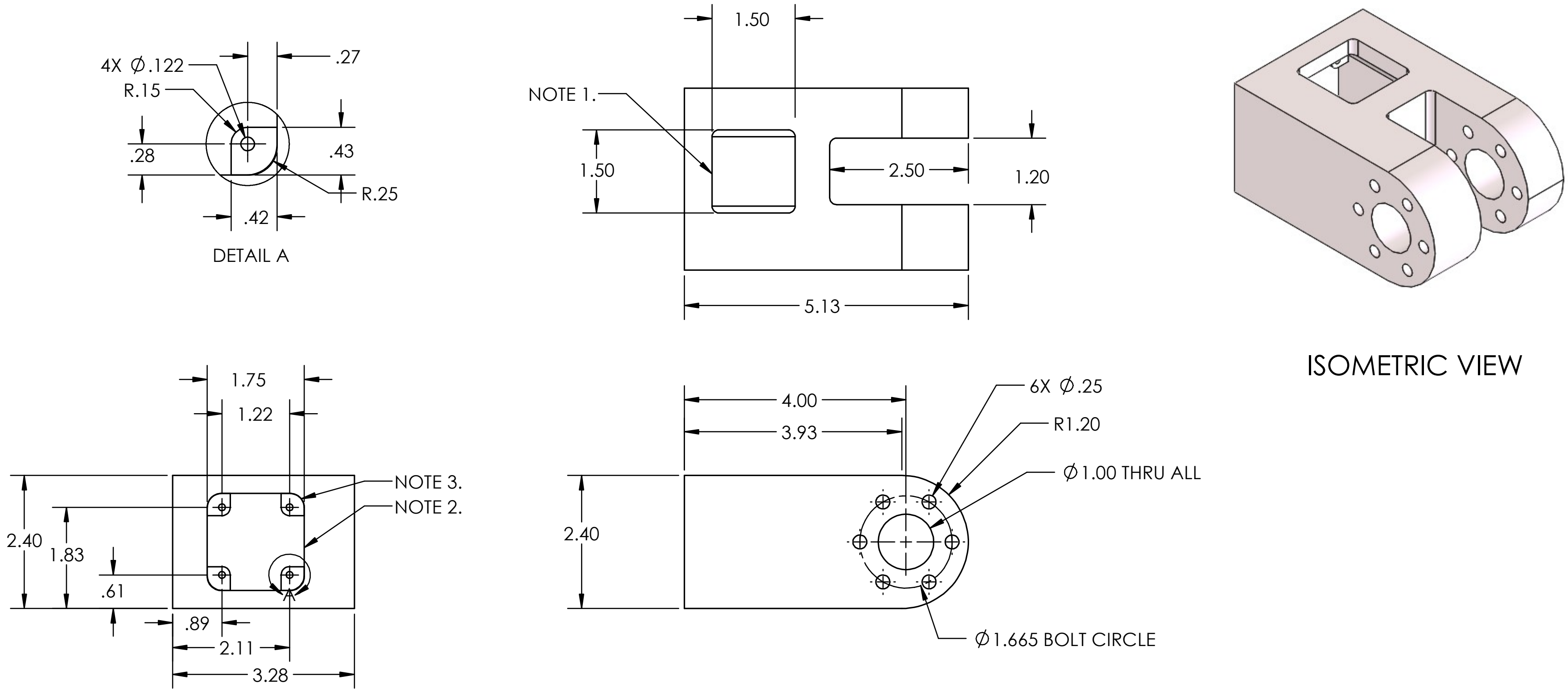
McMASTER-CARR® CAD

PART NUMBER **1230N16**

http://www.mcmaster.com

Corrosion-Resistant HTD
Timing Belt Pulley

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	04/15/2022

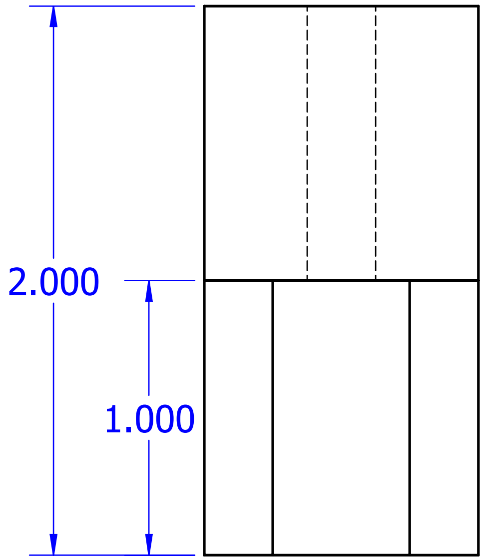


NOTES:

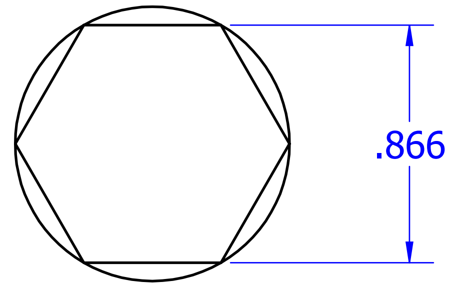
1. THRU CUT.
2. THRU CUT TWO INCHES.
3. CORNER FLANGES WITH THICKNESS OF QUARTER INCH.

TOLERANCES UNLESS NOTED: X.X ± 0.010; X.XX ± 0.005; X.XXX ± 0.001; X.X° ±1°; UNITS:		MICHAEL DECAPUA UNIVERSITY OF COLORADO MCEN 5045
MATERIAL A36 STL		DESCRIPTION WRIST JOINT
FINISH MACHINED	PN 3.01	REV A; SHEET 1 of 1

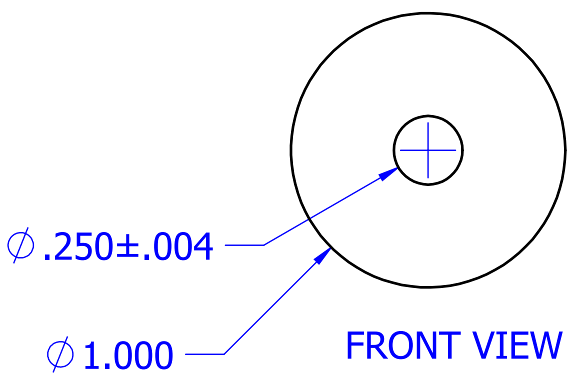
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	17-04-2022
B	TOLERANCES HAVE BEEN SPECIFIED FOR MODEL ASSEMBLY	19-04-2022



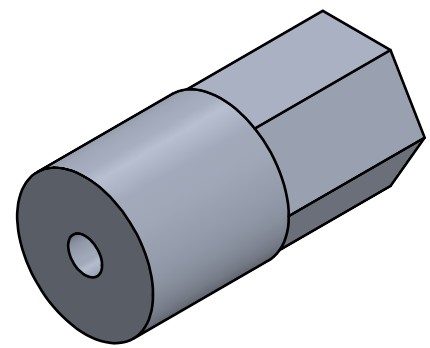
TOP VIEW



BACK VIEW



FRONT VIEW



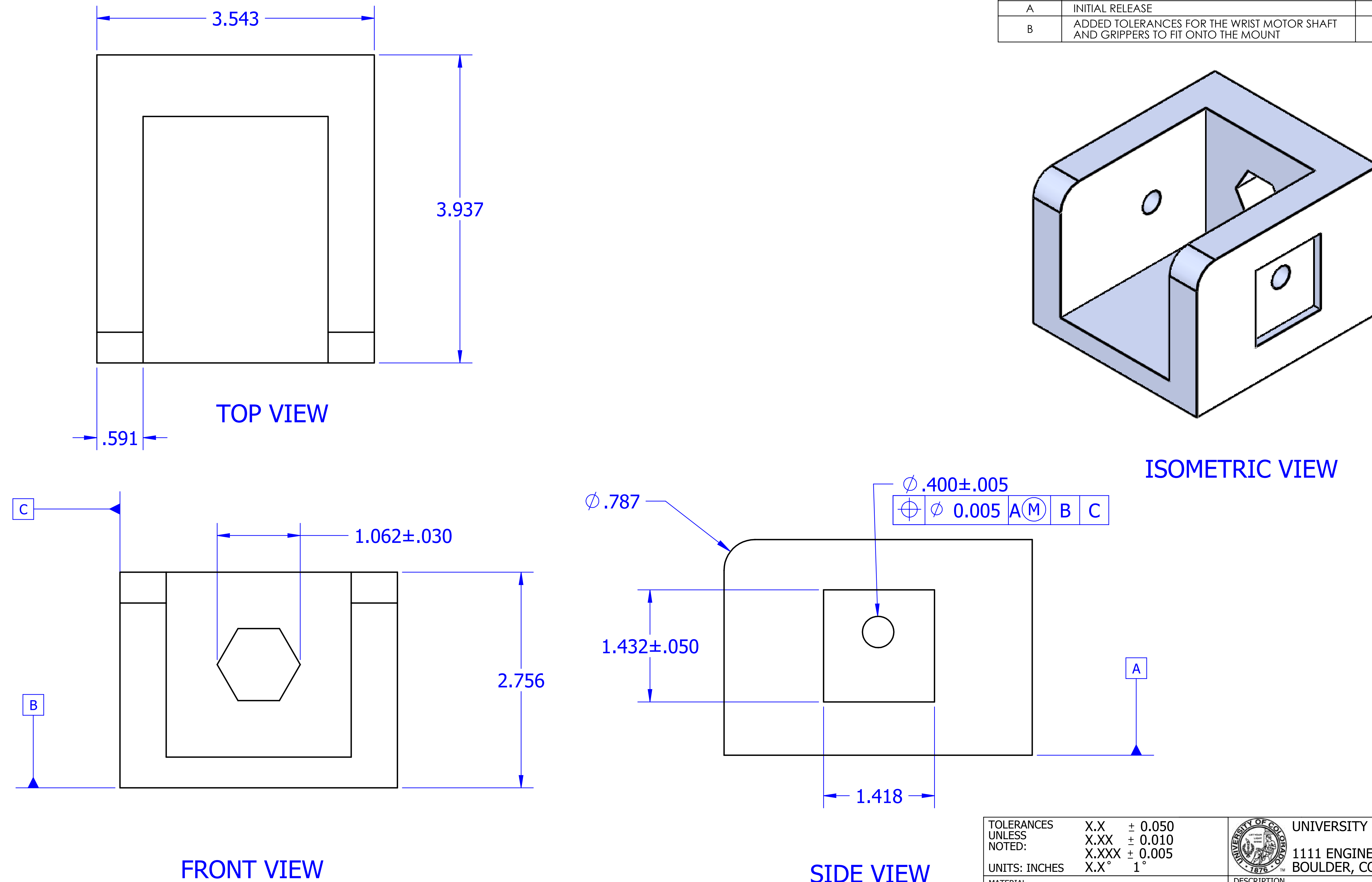
ISOMETRIC VIEW

NOTES:

1. THRU CUT 1 INCH
2. THIS PART SCREWS INTO PART# 4.02 WITH A CLEARANCE OF 0.005 INCH.

TOLERANCES UNLESS NOTED: UNITS: INCHES	X.X ±0.050 X.XX ±0.010 X.XXX ±0.005 X.X° ±1°	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427			
MATERIAL ALUMINUM		DESCRIPTION WRIST MOTOR SHAFT			
FINISH NONE		PN 3.03	REV B		SHEET 1 of 1

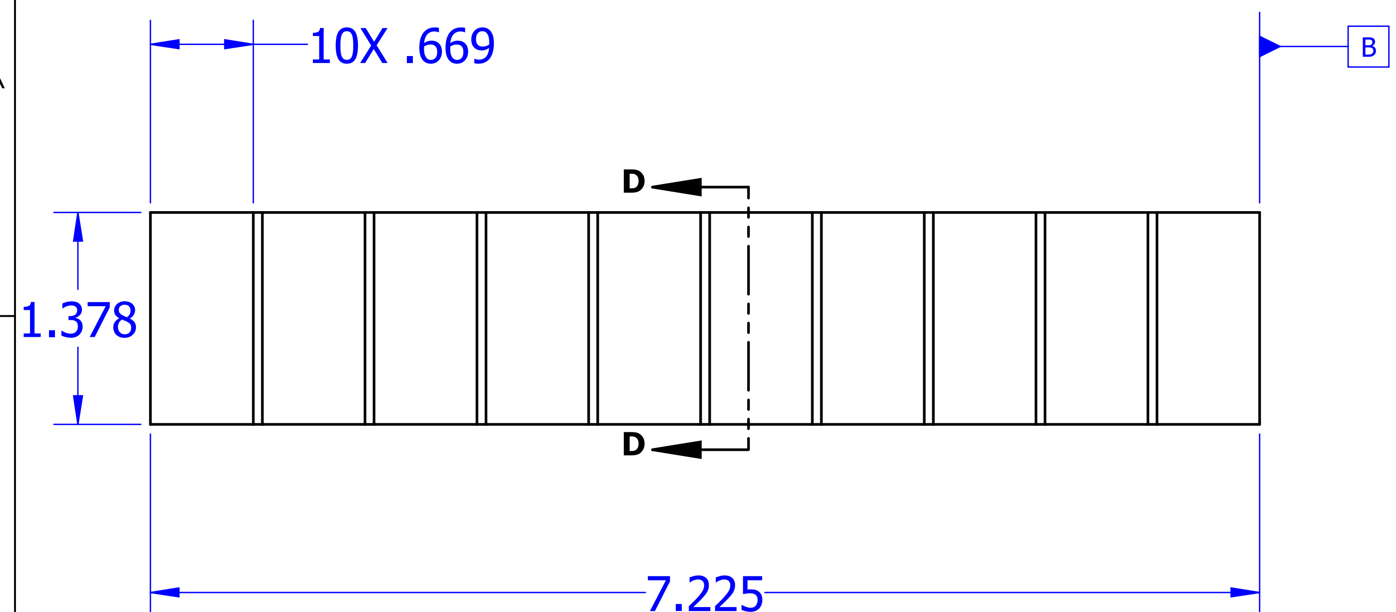
REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	15-04-2022
B	ADDED TOLERANCES FOR THE WRIST MOTOR SHAFT AND GRIPPERS TO FIT ONTO THE MOUNT	19-04-2022

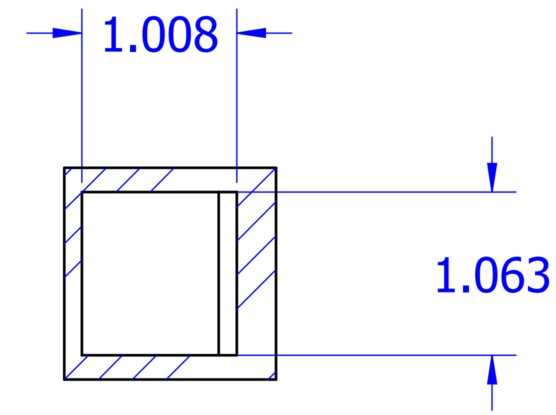


TOLERANCES UNLESS NOTED:	X.X ± 0.050 X.XX ± 0.010 X.XXX ± 0.005	UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427
UNITS: INCHES	X.X° 1°	
MATERIAL 1060 AL ALLOY		DESCRIPTION MOUNTING PLATE FOR GRIPPER
FINISH NONE		PN 4.02 · REV B · SHEET 1 of 1

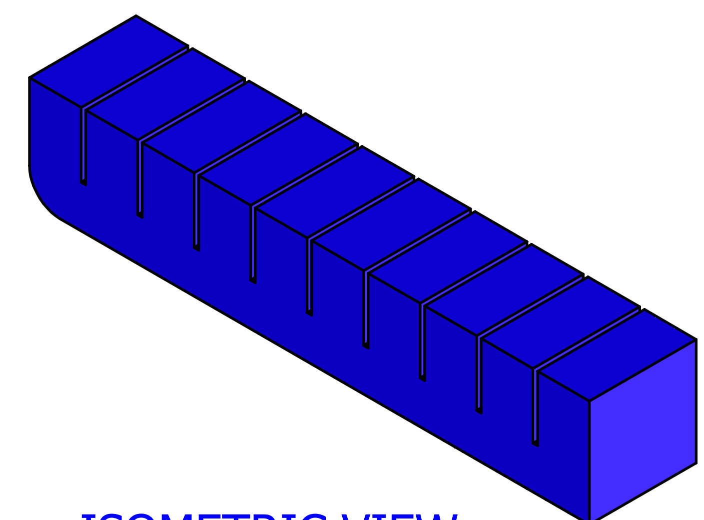
PROPRIETARY AND CONFIDENTIAL THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF UNIVERSITY OF COLORADO. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT WRITTEN PERMISSION IS PROHIBITED.

REV.	DESCRIPTION	DATE
A	INITIAL RELEASE	15-04-2022
B	PNEUMATIC DESIGN UPDATED BY CHANGING THE WIDTH OF THE INNER AIR CHAMBERS	19-04-2022

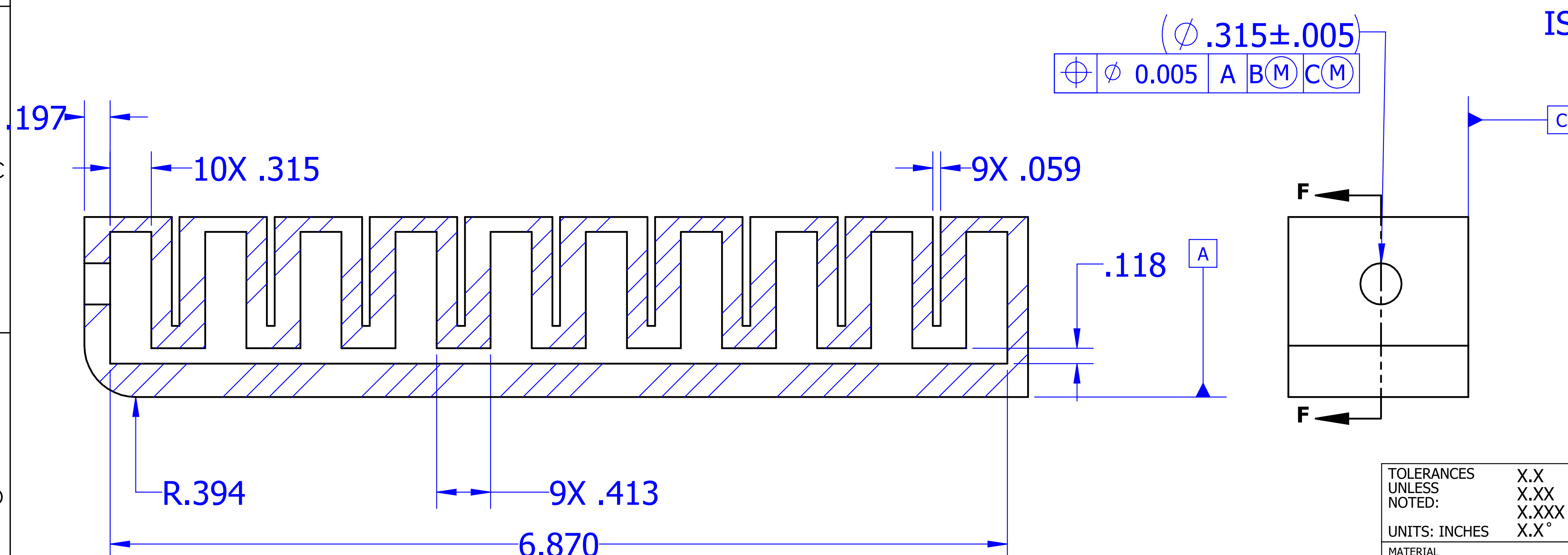




SECTION D-D
SCALE 1 : 1.25



ISOMETRIC VIEW



SECTION F-F

TOLERANCES UNLESS NOTED: X.X ± 0.050, X.XX ± 0.010, X.XXX ± 0.005, X.X° 1° UNITS: INCHES		UNIVERSITY OF COLORADO 1111 ENGINEERING DRIVE BOULDER, CO 80309-0427	
MATERIAL TPU		DESCRIPTION SOFT GRIPPER FINGER	
FINISH NONE	PN 4.04	REV B	SHEET 1 of 1

PROPRIETARY AND CONFIDENTIAL