Final Presentation: Human Robotic Arm Attachment

Los Alamos National Laboratory 4/24

Team: Dalton Boeckmann, Izzy Baumler, Jade Waldron, Morgan Gullo

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Agenda

I. Introduction
II. Problem
III. System Description
IV. Analysis of Design
V. Broader Impacts of Design
VI. Acknowledgements

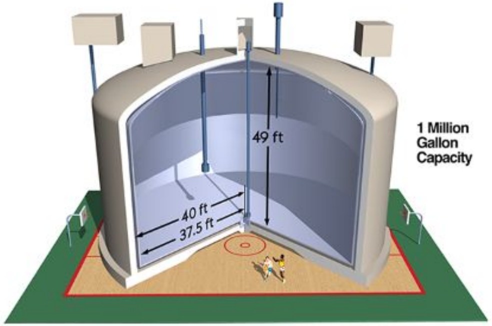
Problem Identification

Location: Hanford Site, Washington State

Background: 45+ years of plutonium production has led to 56+ million gallons of hazardous and radioactive waste stored at the Hanford Site.

Problem: Original tanks designed for 25 years; most now exceed this, with approximately 68 tanks in critical condition.

Risk: High environmental and health risks due to tank deterioration, posing a growing threat to surrounding areas.



Needs Analysis

I. Solution Neutral Problem Statement
II. Mission Statement

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Solution Neutral Problem Statement

- The Solution Neutral Problem Statement (SNPS) serves as the foundation for defining the project's functionality and requirements.
- By focusing on high-level project needs rather than specific solutions, the SNPS was derived.
- The scope of the project and evolving custom requirements prompted regular revisions to the SNPS, ensuring ongoing alignment with project goals.

SNPS	There is a need for a technology that has 5 degrees-of-freedom and can move through 4 degrees-of-freedom of at least 1 Hz.
Customers	Department of Energy, National Research Laboratories

Mission Statement

- Mission statement to clarify the LANL project team's design goals, aligning with both design team and customer needs.
- The mission statement specifies that the LANL project team will design and prototype a 5 DoF robotic arm.

Mission Statement: Human Robotic Arm	
Product Description	Design a 5 DoF robotic arm with human like functionality
Key Business or Humanitarian Goals	Effectively clean nuclear waste from Nuclear Waste Tanks to prevent contamination of local environments and populations Successfully Prototyped and Fabricate Robotic arm within 8 months
Primary Market	Department of Energy
Secondary Market	US Government, US Military, Nuclear Energy
Assumptions	We can assume: that the robot can withstand harsh radioactive environments, the robot can handle large amounts of force without tipping over, the robot can handle large amounts of force without damaging the tank wall, and visibility will allow for sensors to determine if plutonium is being removed, we assume the material is a hard tar heel substance
Stakeholders	Washington Citizens, National Research Labs, Department of Energy
Avenues for Creative Design	Material, robotic actuation for arm movement and control, Semi-Autonomous
Scope Limitations	Resources, only 4 group members, only 8 months to work on it, Size limits, Force limits to protect the tank, Material selection, Dynamic capabilities

Customer Needs

I. Supplemental Design Survey
II. Customer Interviews
III. Customer Needs
IV. Needs Analysis

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Supplemental Design Survey

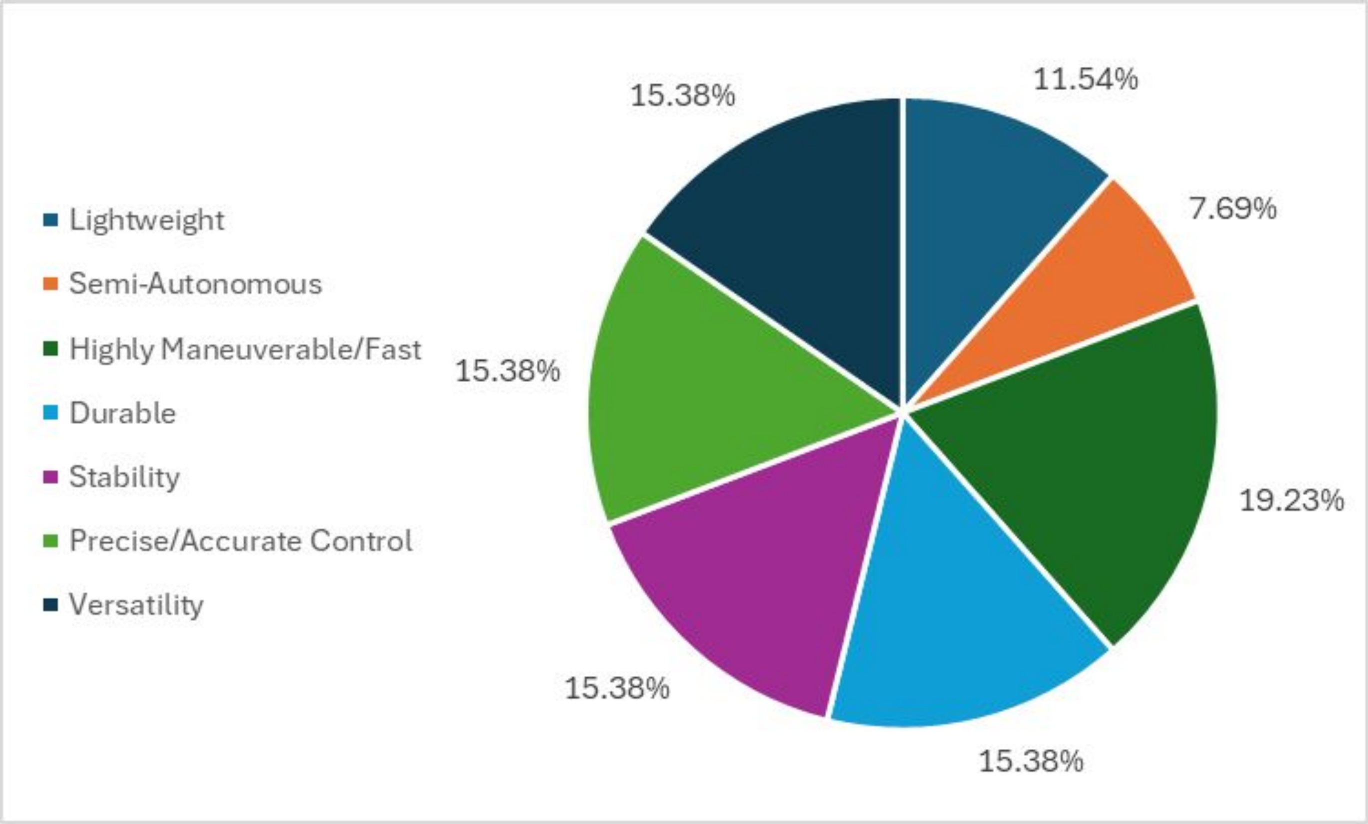
- 13 Respondents of various backgrounds in industry

Please rate the following design feature based on how important you think it is for our arm design: (1= Least Important, 5 = Most Important)
1. Lightweight
2. Semi-Autonomous
3. Is highly maneuverable/Fast
4. Durable under Harsh Conditions
5. Stability (Capability to be highly maneuverable without causing the arm to tip/malfunction)
6. Operates for Long Durations
7. Precise/Accurate Control
8. Versatility (ability to adapt to different tasks, tank geometries, unforeseen obstacles)
9. Do you have any other comments/suggestions/ perspectives the team should consider in the design of our arm?

Customer Interviews

Question	Customer Statement (Rodrigo Ramon)	Customer Statement (Michael Tomlin)	Interpreted Need	Weight	Activity
What specific motions would you expect the robot /robotic arm to handle on a regular basis? (Movement, force)	The robot should be capable of moving back and forth over a specific area during cleaning operations.	The robot needs to perform sweeping motions and accurately identify the edges of curved surfaces on the wall, requiring mathematical precision to navigate these arcs effectively.	The robotic arm must be able to perform repetitive back-and-forth movements over designated areas while also executing sweeping motions to ensure thorough cleaning.	3	Executing precise movement patterns to clean specified areas and navigate curved wall surfaces effectively.

Customer Needs



Customer Needs

- Employed various methods, including preliminary research, customer interviews, and supplemental design surveys to identify and rank critical needs

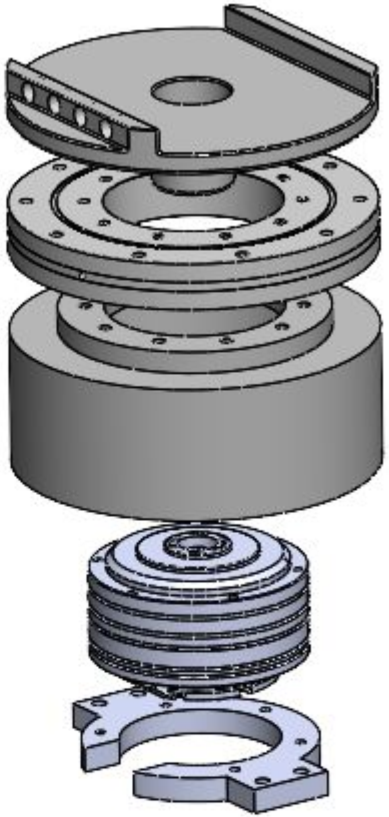
#	Designated Need	Importance Score (1 to 5, 5 = most important)
1	Highly Maneuverable/Fast	5
2	Precise/Accurate Control	4
3	Versatile	4
4	Durable under harsh conditions	4
5	Stable	4
6	Lightweight	3
7	Semi-Autonomous	2

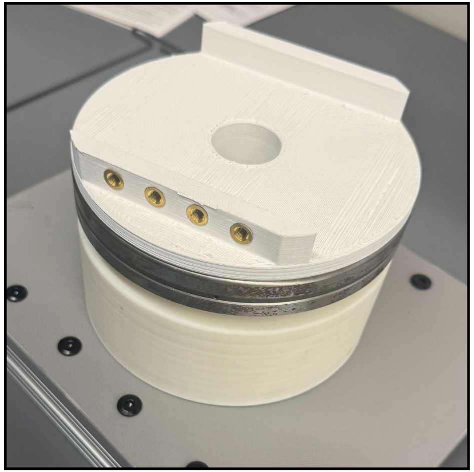
System Description

I. J1 Subassembly
II. J2 Subassembly
III. J3 Subassembly
IV. J4 Subassembly
V. J5 Subassembly
VI. Material Selection
VII. Fastener Selection
VIII. Electrical Selection

J1 Subassembly

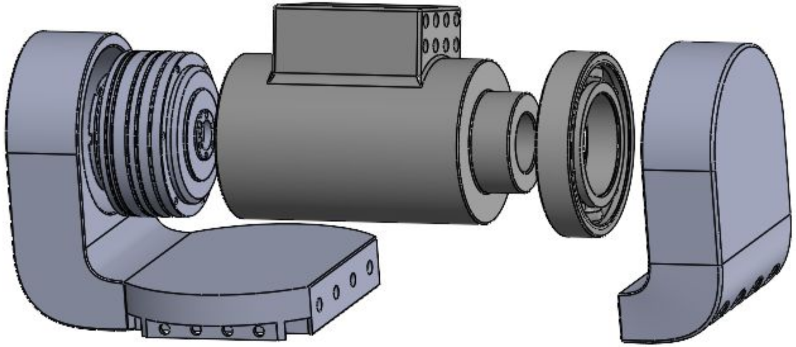
- Holds motor and bearing vertically to handle high torque loads
- Five components: Motor Holder, Mushroom Cap, Motor Cover, Motor, Cross Roller Bearing
- Cross-roller bearing reduces friction and distributes load to prevent motor shaft failure
- Uses clearance fit holes (M4-M6) for easy assembly
- Adjusted hole tolerance from 0.4mm to 0.6mm for better fastener fit





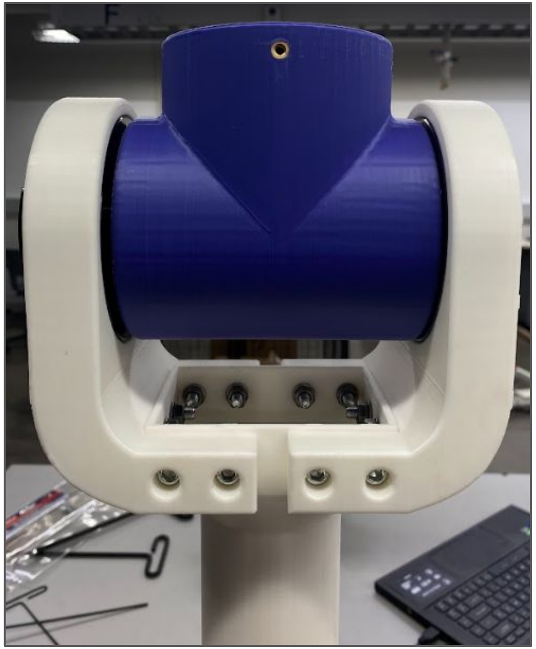
J2 Subassembly

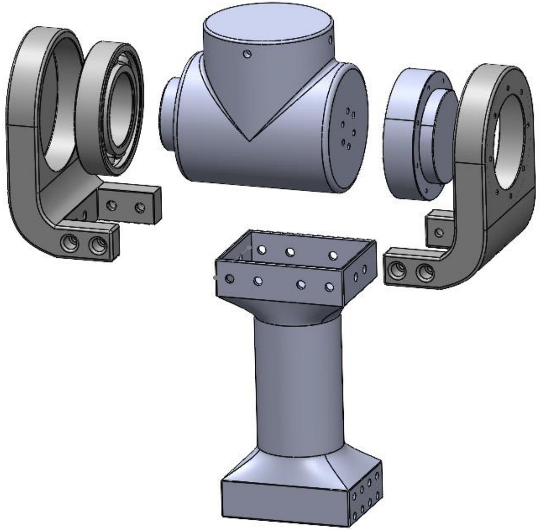
- Provides up-and-down movement to expand the arm's workspace
- Motor and bearing mounted on opposite sides of a cylinder for connection
- Five components: Motor Holder, Motor, Ball Bearing, Bearing Holder, Cylinder
- Essential for reaching different heights without repositioning the base



J3 Subassembly

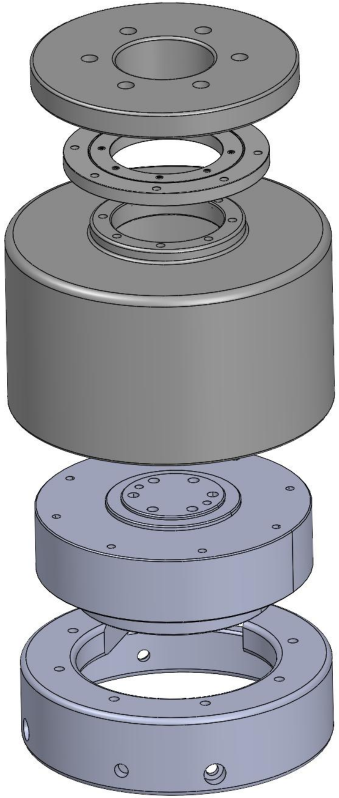
- Functions like a human elbow for vertical movement
- Six components: Bicep, Motor Holder, Motor, Ball Bearing, Bearing Holder, Cylinder
- Uses a similar design to J2 for simplicity
- Smaller motor and bearing due to weight constraints
- Enhances dexterity and efficiency in robotic motion

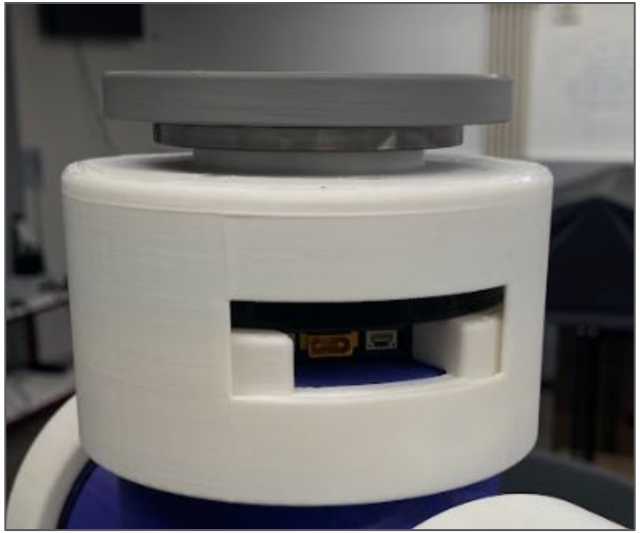




J4 Subassembly

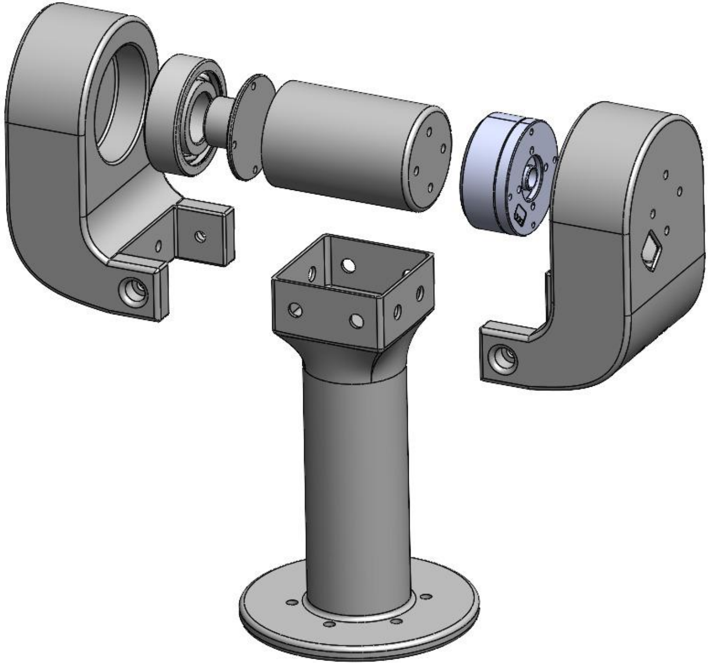
- Enables rotational movement similar to a human elbow
- Five components: Motor Holder, Motor Cover, Cross Roller Bearing, Mushroom Cap, Motor
- Similar function to J1 but connects to J3 Cylinder instead of the base
- Uses the same motor as J3 for consistency



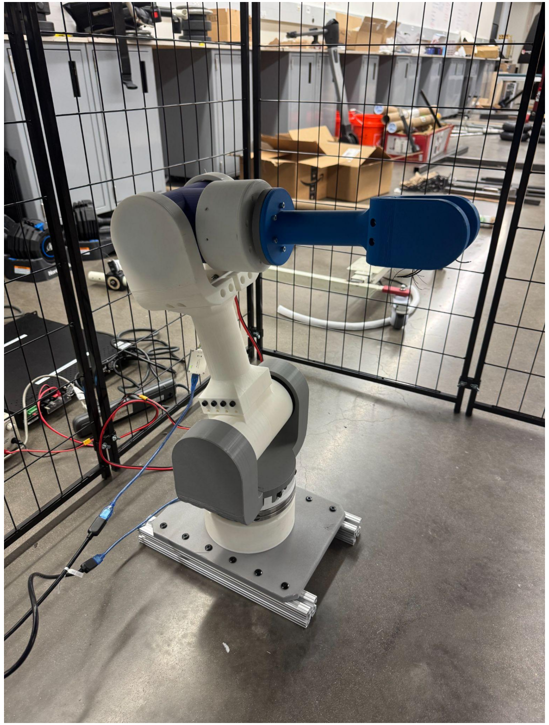


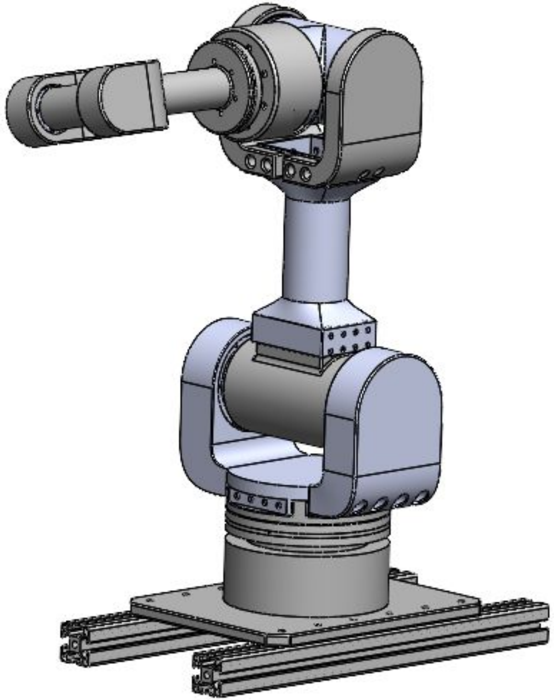
J5 Subassembly

- Provides wrist-like up-and-down motion for fine control and dexterity
- Seven components: Forearm, Motor Holder, Bearing Holder, Cylinder, Cylinder Cap, Motor, Bearing
- Allows end-effector to tilt and interact with objects effectively



Fully Assembled Robotic Arm





Material Selection

- **PLA**: Used for prototyping due to ease of printing, low cost, and accuracy
- Experimental Procedure:
  - Measured the PLA sample with calipers
  - Set grips at 25 mm from each end of the sample
  - Set test speed to 5 mm/min
  - Measured elongation of sample after plastic deformation was reached
- Yield strength of about 14.8 MPA

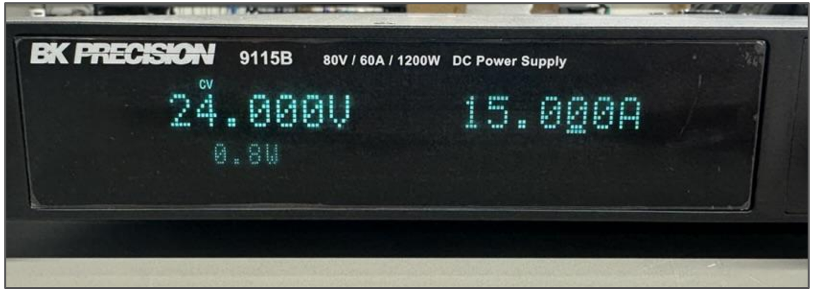
Fastener Selection

Constraints:
- Motor Sizing (M2.5 - M6)
- Bearing Sizing
- Cost Effectiveness
- Vibrational Conditions

Identification of Socket Head Cap Screws
- High tensile strength - (170,000 psi)
- Applicable in High Torque environments
- Compatible with heat set inserts in PLA to prevent loosening

Cost ~ 300$
Sizing ~ (M2.5 - M6) & (4 - 30 mm)
Tensile Strength ~ 170,000 PSI

Electrical Selection



BK PRECISION

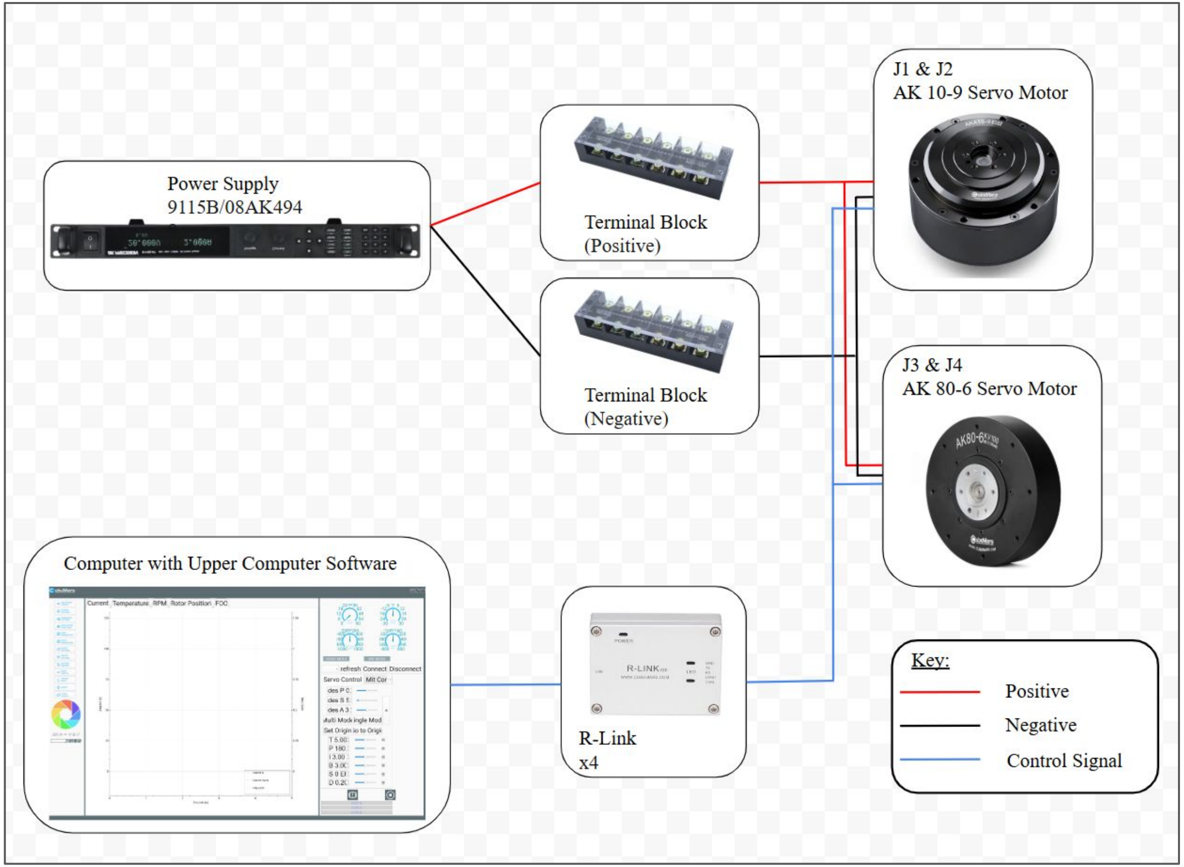
9115B

Bench Power Supply, Programmable, 1 Output, 0 V, 80 V, 0 A, 60 A

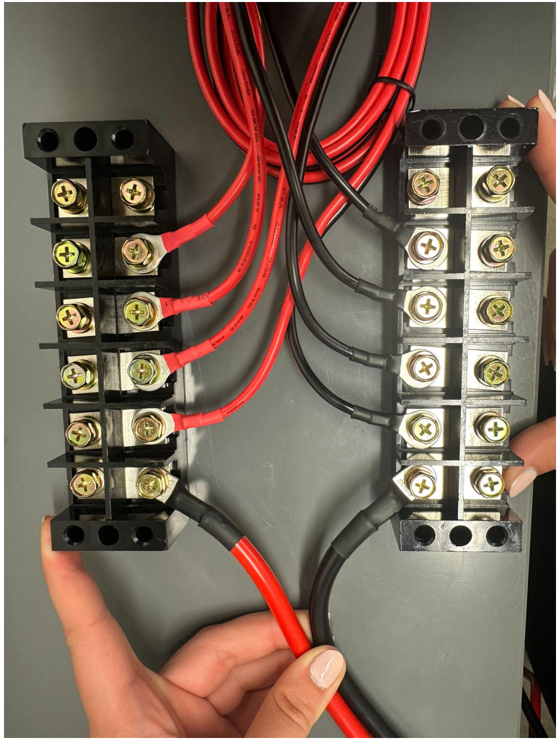
Manufacturer	B&K PRECISION
Manufacturer Part No	9115B
Newark Part No.	08AK4948
Product Range	9115B Series
Technical Datasheet	Data Sheet

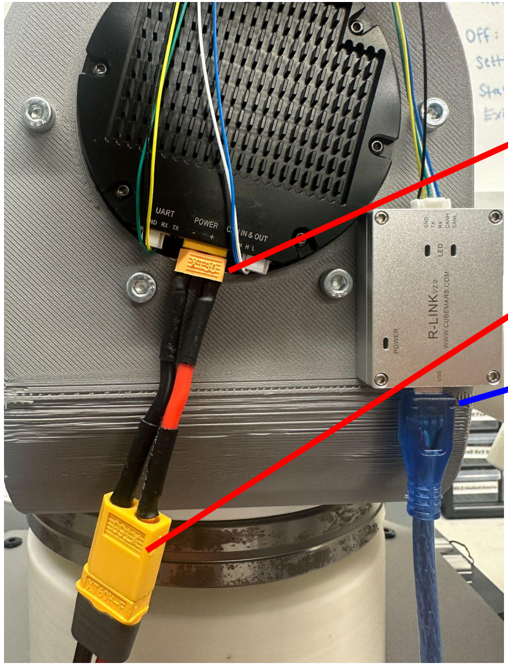
See all Technical Docs

Electrical Selection



Electrical Selection



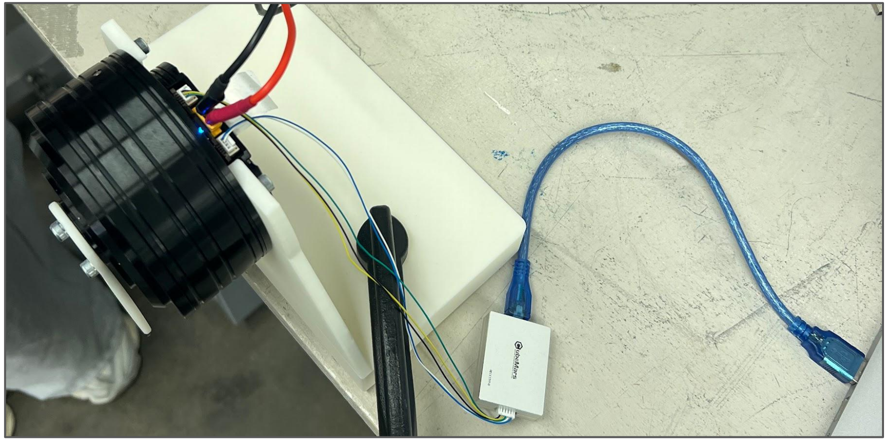


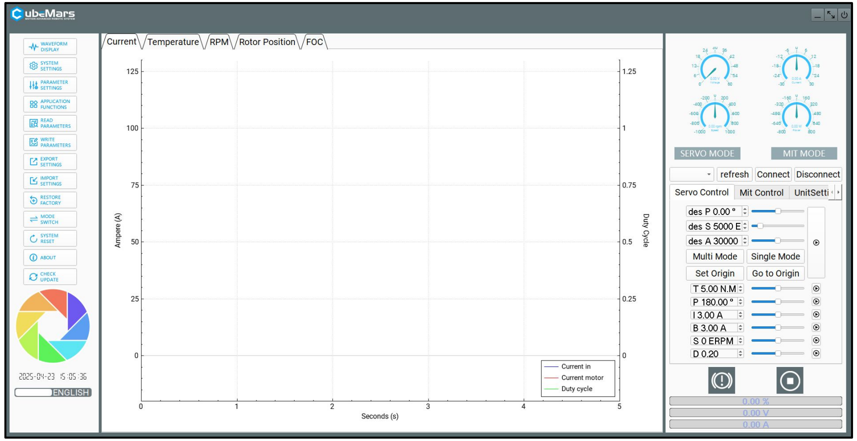
XT30 - XT60 Converter

USB to common hub

Control Selection

- Utilized a CubeMars device called “R-Link”
  - Serial-to-USB communication device
- Facilitates connection to the motors' Upper Computer software for setup and control.





Analysis of Design

I. Embodiment Design Checklist
II. Risk Analysis (FMECA and FTA)
III. DFMA
IV. Design Validation
V. Comparison of Design
VI. Cost Accounting and Cost Model

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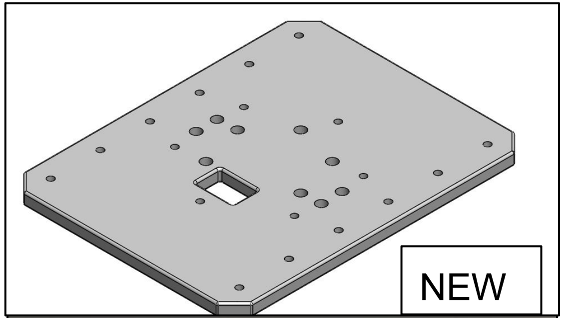
Logistical Challenges Faced

Design Complexity & Iteration:

- Realization of design complexity during fabrication
- Necessity for iterative redesign of components

Manufacturing & Assembly Issues:

- Tolerance issues with threading PLA and heat-set inserts
- Importance of infill percentage for 3D-printed part strength
- Impact of print orientation on dimensional accuracy
- Clearance problems with press-fit fasteners, requiring base redesign



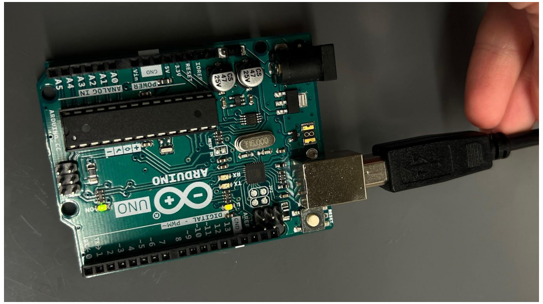
Logistical Challenges Faced

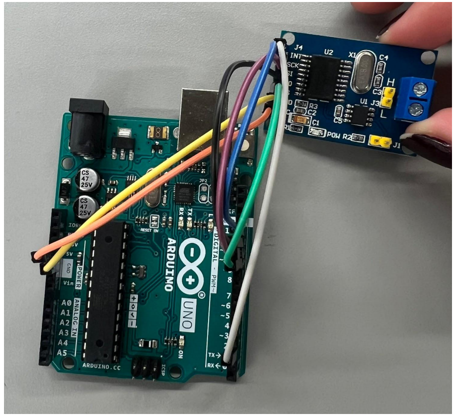
Motor Control Challenges:

- Difficulties with Arduino to CAN Bus connection.
- Limited C language expertise leading to control delays.
- Successful individual motor testing via R-link and upper computer
- Goal to continue to troubleshoot the Arduino to CAN connection

Budgeting & Outsourcing:

- Unexpected tariff fees impacting project budget. (500$)
- Cancel further foreign orders
- Successful acquisition of components through LANL sponsorship





Embodiment Design Checklist

Project Team Name: LANL Human Robotic Arm Capstone						
Team Members: Izzy Baumler, Dalton Boeckmann, Morgan Gullo, Jade Waldron						
Attribute	**Embodiment Design Checklist Item**	**% Complete**	**Status of Design**	**Unresolved Issues**	**Get-well / Recovery plans, and Responsible Person**	**Expected Resolution Date**
Function	Are the customer needs satisfied, as measured by the target values? Is the stipulated product architecture and function(s) fulfilled? What auxiliary or supporting functions are needed?	100%	The team has incorporated 5 motors into the design to account for the 5 degrees of freedom wanted by the customer. To meet the speed requirement very fast brushless DC motors are being utilized to increase the speed of the robotic arm. The speed of one rotation can be measured once joints have been assembled. Supporting functions would be the electricity needed to power the motors as well as the motors being able to operate with the attachement of 3D printed parts.	Issues will occur as assembly begins. The issue of obtaining a power source to supply each motor needs to be resolved	Redesigning the CAD, printing with stronger filament, borrowing power source from TAMU facilities. Entire Team	March 1, 2025
Working Principles and Form solutions	Do the chosen form solutions (architecture and components per function) produce the desired effects and advantages? What disturbing noise factors may be expected? What byproducts may be expected?	100%	The team has finished the full prototype and is in the process of printing parts. Motors are being tested to check working principals. Analysis has been performed on the robot structure to ensure it can hold itself up and work properly. There may be mechanical noise from the brushless DC motors or vibrations created from turning the robot very fast. A byproduct of heat from the motors may be expected.	Figuring out how to get the motors to move simultaneously. Assembling the robot and iterating through parts that have unexpected problems or don't fit properly.	Consulting experts who have experience with these motors. Printing joints with stronger filament if they begin to break under stress. Entire team	March 1, 2025
Layout, Geometry, and Materials	Do the chosen layout, component shapes, materials, and dimensions provide minimal performance variance to noise (robustness), adequate durability (strength), efficient material usage (strength to mass ratio), suitable life (fatigue), permissible deformation (stiffness), adequate force flows (interfaces and stress concentrations), adequate stability, impact resistance, freedom from resonance, unimpeded expansion and heat transfer, and acceptable corrosion and wear with the stipulated service life and loads?	100%	The chosen layout, component shapes, materials and dimensions have provided us with the multiple of the requirements mentioned on the left. At this stage of our robot, it is difficult to quanity some of these metrics. As the robot progresses we will evaluate these metrics and ensure that progress is being made towards them to ensure an efficient robot arm.	We plan on using PET-G instead of PLA for final print but will get final confirmation from our sponsor soon.	We will evaluate if certain metrics are failing and make adjustments if time/money allows. Jade	March 1, 2025
Energy and Kinematics	Do the chosen layout and components provide efficient transfer of energy (efficiency), adequate transient and steady state behavior (dynamics and control across energy domains), and appropriate motion, velocity, and acceleration profiles?	100%	An electrical layout was created to mitigate the need for a very strong battery to power the motors needed for the robot. Brushless DC motors were chose in order to achieve the motion, velocity, and acceleration profiles wanted by the sponsor. Calculations have been conducted on the steady state behavior to ensure the robot can maintain stability at steady state . The weight of the robot and strength of materials were analyzed.	The behavior of the movement of the robot still needs to be addressed. The motion of the robot needs to be evaluated as the robot is assembled.	Moving motors individually to ensure proper movement and acceleration. Reprinting parts with stronger material if steady state is not acheivable with the current design. Izzy & Dalton	March 1, 2025
Safety	Have all of the factors affecting the safety of the user, components, functions, operation, and the environment been taken into account?	100%	The team has ordered a safety cage (dog kennel) per request from our sponsor. This will properly enclose the robotic arm during testing to ensure no one gets injured. We will also implement a kill switch if the robotic arm malfunctions or becomes sentient.	The kill switch has not been factored into the electrical.	Morgan	March 1, 2025

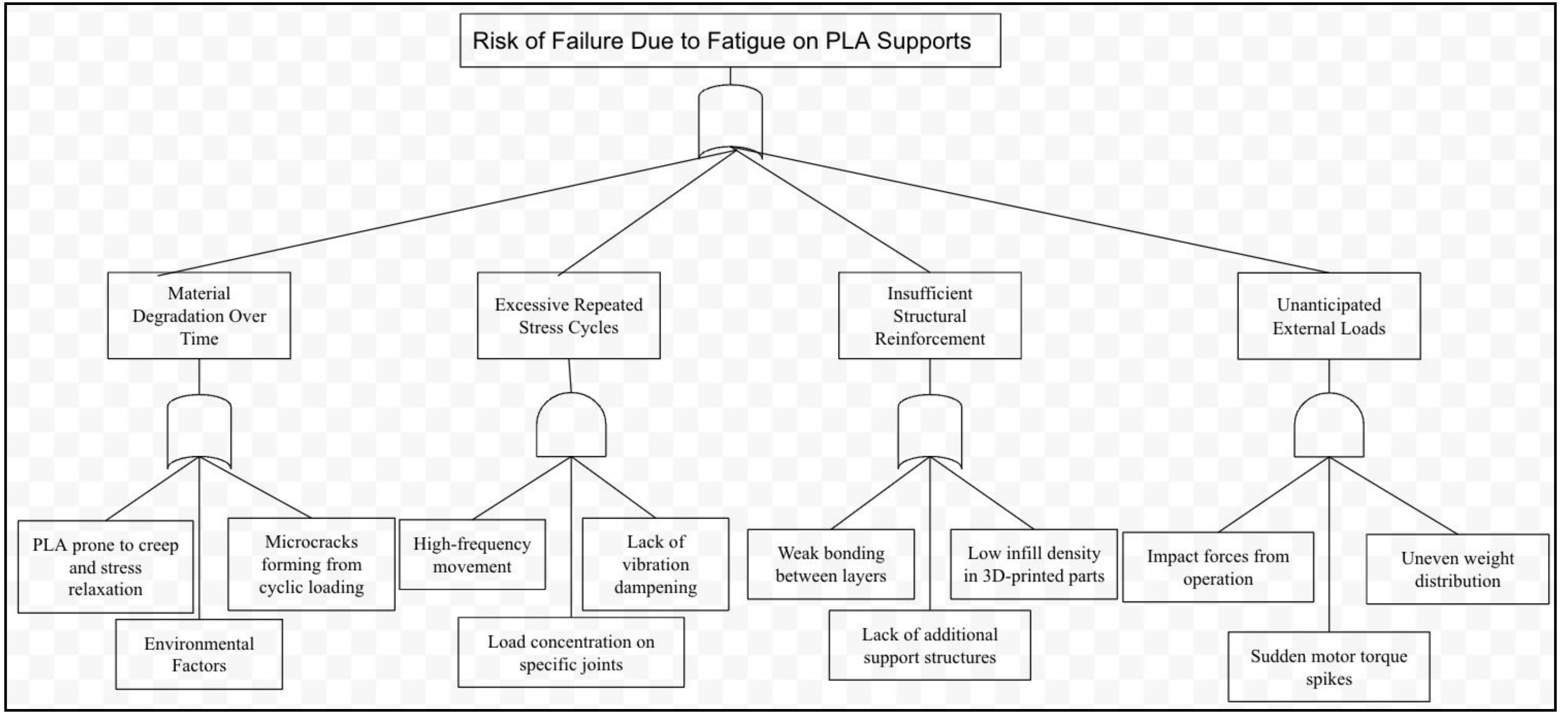
Failure Modes, Effects, and Criticality Analysis (FMECA)

		Assessment							Recommended Actions	
Part # and Functions	**Potential Failure Mode**	**Potential Effect(s) of Failure**	**Severity (S)**	**Potential Causes and Mechanisms of Failure**	**Occurrence (O)**	**Current Design Controls Test**	**Detection (D)**	**RPN**	**Description of Action**	**Responsibility & Target Completion Date**
J1 Motor (AK10-9 V2-0): converts electrical energy into mechanical motion to control joint movement, positioning, and speed for precise operation *****Repeat for J2, J3, J4, and J5 motors**	Bearing wear and tear (Bearings within the motor) can experience friction which leads to gradual wear. If the bearing is exposed to excessive loads it can seize.	As the bearing wears, the internal components of the motor may start rubbing together or misalign, generating more friction. This increases the likelihood of the motor shaft becoming stuck, resulting in seizing. The sound has a possibility of being loud indicating malfunction. The motor seizing could result in flying debris damaging surrounding equipment. Lastly, a seized motor has the possibility of causing erratic or inconsistent movement.	8	Improper assembly	4	Performing Interface Checks in CAD to identify areas where misalignment could occur	2	64	Perform interface checks in CAD and with 3D printed parts and update assembly guide accordingly	Jade
				Impact Loading	4	We performed Stress tests on the PLA to ensure the parts can withstand loads in tangent with the motor	3	96	Update the design to allow for impact-resistance filament if PLA fails	Jade
				Overstressing	2	We calculated the torque requirements of each joint to prevent the motor from over torquing.	4	64	Perform torque calculations and design updates to motor and joints	Dalton
				Poor Maintenance	2	An ideal solution would be to have automatic alerts that track the motors performance over time. \	4	64	Implement automatic diagnostic systems and ensure they interface with motor control system	Izzy
J1 Cross Roller Bearing (2010N16): provides high-precision rotational support by evenly distributing loads in multiple directions, ensuring smooth, stable, and accurate movement of joints while minimizing friction and deformation *****Repeat for J2, J3, J4, and J5 bearings**	Housing or Mounting Weaknesses – If the bearing is not properly integrated into the robotic arm structure, misalignment or uneven load transfer can lead to premature wear or failure	-Reduced Precision -Excessive Vibration or Noise -Increased Friction -Structural Damage	7	Improper Alignment during assembly	4	Complete Alignment testing by conducting visual or automated inspection system checks; verify/integrate tolerances during design	3	84	Develop an alignment checklist for assembly teams to follow	Jade/Dalton
				Material degradation	6	Conduct material testing such as hardness, tensile strength, and fatigue testing to ensure material can withstand long-term use	2	84	Perform fatigue testing on "sample" housing that has similar shape/thickness	Izzy/Morgan
				Overloading	2	Conduct load testing by applying varying levels of stress and forces beyond normal operational capacity	4	56	Perform physical load testing beyond normal operating conditions on "sample" housing that has similar shape/thickness	Izzy/Morgan

Failure Modes, Effects, and Criticality Analysis (FMECA)

PLA supports, joints, and foundation base: supports provide temporary structural stability for overhangs and complex geometries, joints enable part connectivity and mechanical movement through designs like snap-fits or hinges, and the base ensures strong bed adhesion to prevent warping and print failure	Brittle Fracturing - under stress, PLA has low impact resistance and can crack or snap under excessive force, particularly at joints or thin support structures.	Loss of Functionality – Fracturing at joints or supports can cause parts of the arm to disconnect or become immobile, disrupting its intended operations and possibly rendering it inoperable.	8	Brittle Fracturing	5	Perform mechanical stress testing by applying controlled forces using a universal testing machine	3	120	Begin investing/researching in a stronger filament such as ABS or PETG for high-stress components	Jade
				Inadequate Print Quality	3	Perform dimensional accuracy and layer bonding tests while also identifying weak spots caused by poor layer bonding	5	120	Optimize print settings (such as higher infill density and wall thickness) and ensure proper layer bonding on 3D printers	Dalton
				Exposure to High Temperatures	2	Conduct heat resistance test by exposing parts to a temperature chamber for varying temperatures	2	32	Begin investing/researching in a stronger filament such as ABS or PETG for higher-temperature environments	Jade
				Fatigue from Repeated Motion	6	Conduct fatigue testing by using a motion test rig to simulate repetitive cycles	3	144	Begin investing/researching in using Nylon or TPU for parts subjected to repeated motion	Morgan
Metal Fasteners: secure components together, provide structural stability, enable adjustments and repairs, ensure precise movement and alignment, and facilitate load distribution to prevent failure under stress	Complete bolt or screw shearing or thread stripping - cause critical joint failure, resulting in the disconnection of components, loss of functionality, and potential damage to other parts or injury during operation	Complete loss of control and function of the robotic arm	9	Over-tightening /Under-tightening	3	Perform a torque test to ensure the fastener is tightened to the correct torque specification	2	54	Implement torque-limiting features/self-locking fasteners to prevent over/under tightening	Dalton
				Fatigue from Repeated Motion	5	Perform fatigue cycle testing to simulate the effect of repetitive loading on fasteners	3	135	Implement a design for load distribution and use reinforced fastener placements	Izzy
				Material Defects	3	Perform non-destructive testing to detect internal material defects that could weaken the fastener	5	135	Implement premium materials with higher quality control	Morgan
				Corrosion/Environmental Exposure	2	Conduct corrosion resistance testing to test the fastener's ability to withstand environmental factors like moisture and chemicals	3	54	Apply protective coatings to fasteners to enhance their resistance	Dalton

Fault Tree Analysis (FTA)

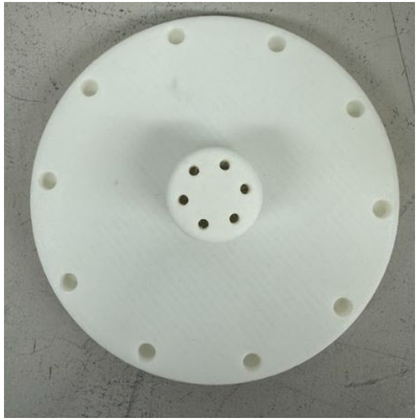


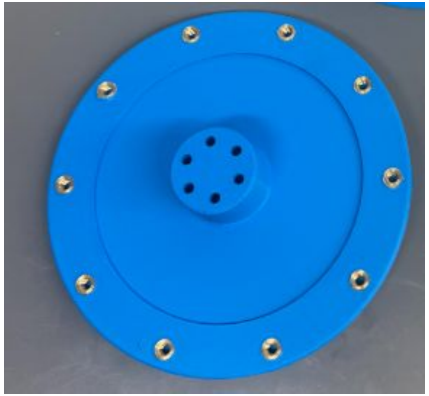
Standards and Codes

Code	Implication
FMECA- (ISO 10218-2:2025) [7]	Failure mode and effects analysis which provides a systematic process for identifying potential failures in a design, process, or product. Assessing their severity occurrence, detection capability, and actions to mitigate risks. Addresses robots integrated into machinery (robot applications and cells).
Environmental Protection Agency - (40 CFR Part 191) [1]	Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation, based upon performance assessments, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall
Federal Land Disposal Requirements (40 CFR Part 268) [2]	Generators and treatment facilities that ship mixed waste for disposal at the Hanford Site must do the following to demonstrate compliance with LDR regulations
The Washington State Dangerous Waste Regulations (WAC 173-303) [3]	The Washington State Dangerous Waste Regulations (WAC 173-303) regulate a broader universe of waste than the RCRA regulations and have additional land disposal restrictions. Waste generators and treaters must understand Washington's regulations as they apply to the disposal of waste.
IAEA-TECDOC-672 (Section 4) [4]	Robotic System Applications - Addresses the potential use of robotic technology as it relates to different modes of plant operation
ISO 10218 [5]	Safety requirements for industrial robots
USDL OSHA Standard 1915.181 [6]	Electrical circuits and distribution boards

DFMA

- Over 40 custom 3D-printed parts across 5 subassemblies prioritized ease of assembly and repeatable manufacturing
- Standardized M2.5–M6 screws and used counterbored holes to avoid clearance issues.
- Switched from heat-set inserts to open nut-and-bolt method for bicep/forearm to reduce print failures and time spent soldering
- Added bearing divots in J1 and J4 to reduce PLA friction and prevent deformation.





DFMA

- Used ~1 mm fit tolerances for ball bearings in J2, J3, and J5 to ensure secure seating.

- J1 and J4 share mirrored components; J2, J3, and J5 follow a cylindrical architecture.

- Reused motor holders, bearing mounts, and fastener strategies to reduce part variability and streamline prototyping.

Design Validation: Individual Motor

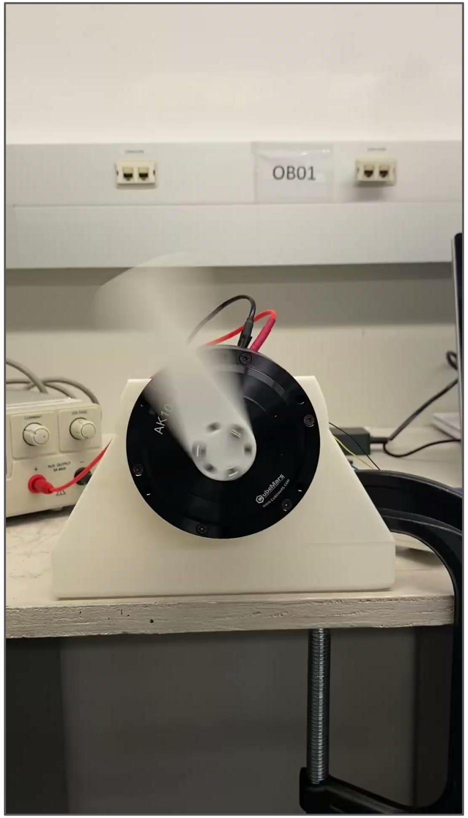
Motors tested **individually** and **within full assembly**.
Target actuation frequency: **1 Hz (6.28 rad/s)**.
Upper Computer required **rad/s**, not Hz → all inputs converted.
Control gains tuned for performance:

- **Position:** Kp = 3, Kd = 1 → Fast + stable convergence
- **Speed:** Kp = 0, Kd = 0.5 → Damped motion, minimal overshoot
- **Torque:** Kp = 0, Kd = 0 → Direct current control for holding

Motors tested on a custom stand Verified:

- **Angular positions:** 0°, 90°, 180°, 360°
- **Speed:** Up to 6.28 rad/s
- **Torque:** Verified Motors could output necessary torque

Motors J1–J4 showed consistent, accurate responses via Upper Computer.



Speed - 6.28 rad/s

Design Validation: Integrated

- Motors tested in assembly (J1 → J4)
- Testing divided into three categories in order to validate the robotic arm at full operation:
  - Positional Verification: 0°– 360°
  - Speed Verification: 1 Hz Frequency
  - Torque Verification: Max Loading Scenario (Full Extension)

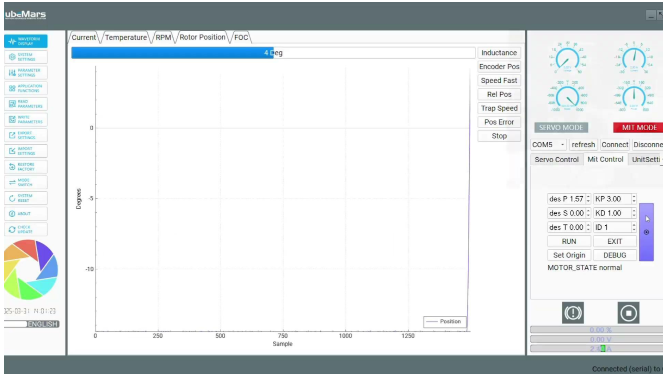
Positional Testing

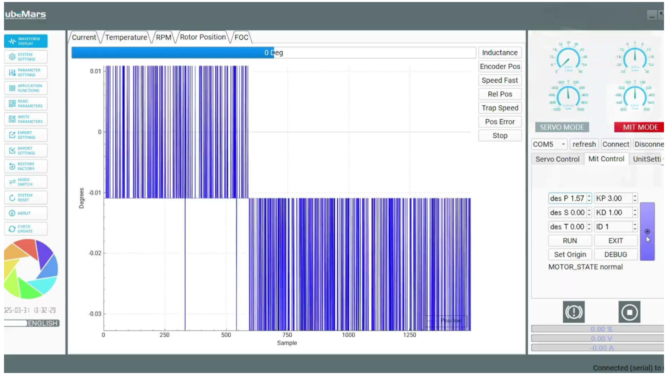
Each joint was tested across its full range of motion, starting from 0° to the following maximum angles:

- **J1**: 0°– 360°
- **J2**: 0°– 180°
- **J3**: 0°– 180°
- **J4**: 0°– 360°

Consistent ~20° offset was observed during position control testing for all joints.

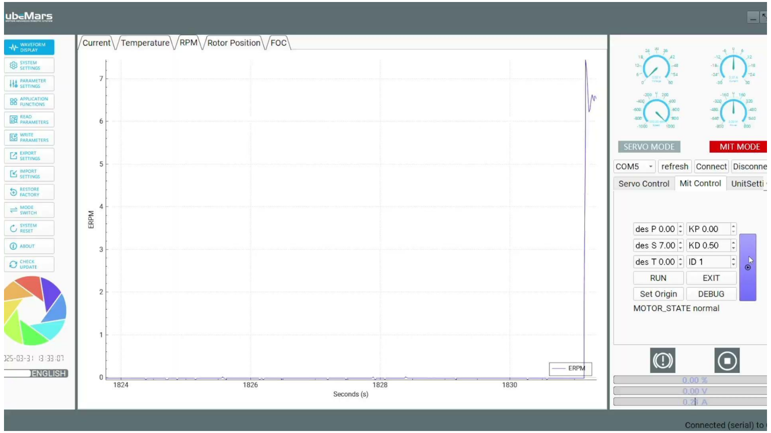
The deviation across all joints strongly indicated that the issue originated from the Upper Computer, rather than individual joint configuration.



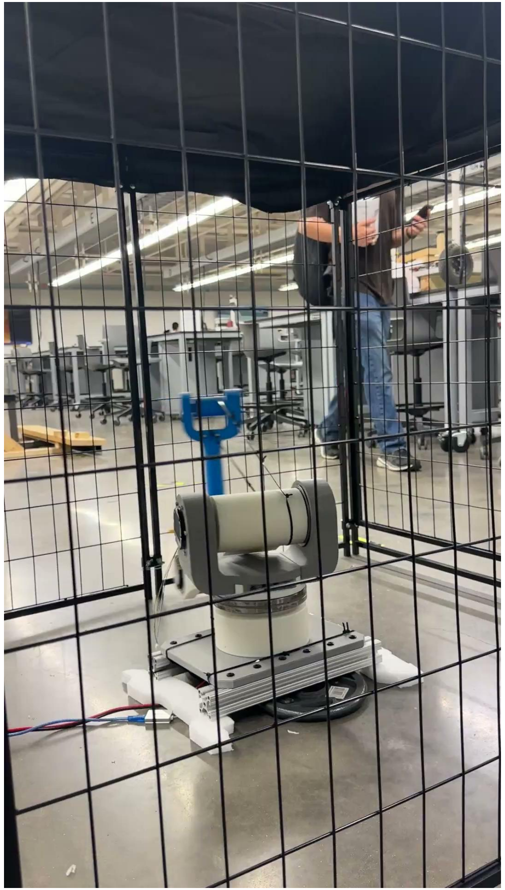


Speed Testing

- Speed tested on integrated system using specific motor types (J1 and J4)
- **J1 and J4** verified to achieve **1 Hz (6.28 rad/s)**
- Initial tests showed **undershoot** due to added load from robot assembly
- Undershoot was caused by the increased load and resulting torque demand on the motors due to the added mass and inertia of the assembled robot.
- Increased iteratively and final output confirmed actual **speed matched 1 Hz target**

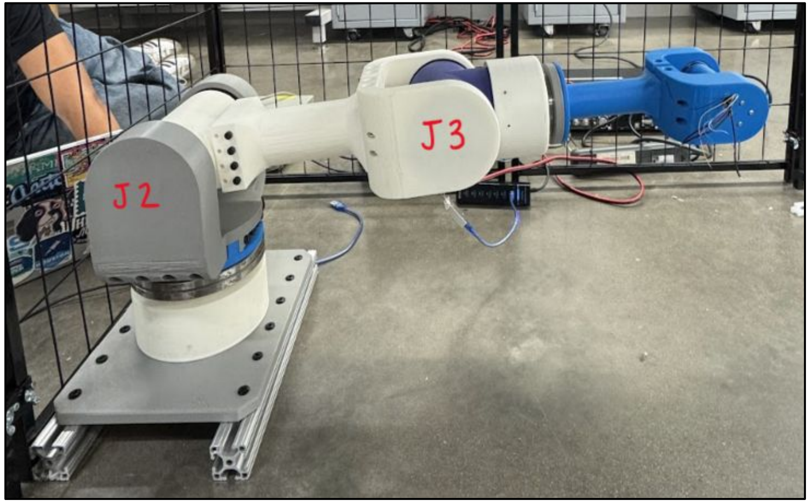


Speed Testing



Torque Testing

- Robotic arm loading varies significantly in 3D space, making full-case testing impractical
- Team focused on worst-case scenario: **maximum torque at horizontal full extension (0.72 m)**
- Joints **J2 and J3** identified as most affected under this condition
- Torque testing was based on this maximum-load scenario, full extension at 0.7 m
- Original payload calculations were used to generate torque input values for the upper computer and verified during testing



Joint	Calculated Torque (N-m)	Actual Torque (N-m)
J2	21.33	20
J3	3.74	2

Design Validation

Weight: 11.88 kg (26.2 lb), **under** the 14 kg max.

Torque:

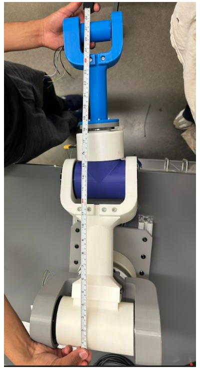
- **J2 (high-torque joint)**: 20 Nm using [AK 10-9 Motor]
- **J3 (low-torque joint)**: 2 Nm using [AK 80-6 Motor]

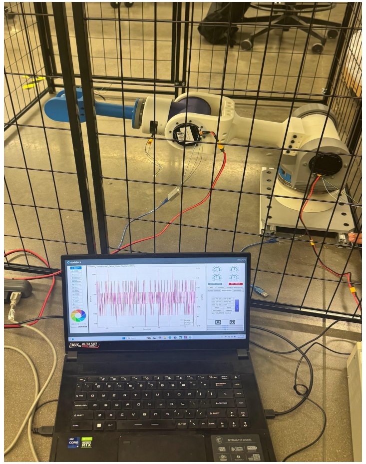
These values confirm our motors can support joint loads, especially in demanding positions.

Accuracy: While mm-level measurements were limited, all motors responded reliably and consistently to positional commands during software-controlled testing.

Reach: Achieved a reach of **0.87 m**, exceeding the minimum required (0.67 m).

Mass Distribution: Calculated as **0.132 kg/cm**, outperforming the 0.209 kg/cm threshold.





Comparison of Design

- All design requirements were satisfied as confirmed through validation testing
- Critical sponsor requirements: rapid movement and sustained motion at 1 Hz
  - Motor tests at each joint confirmed required speed (m/s) and frequency (Hz)
- Demonstrated speed, precision, and reliability, fulfilling sponsor's top priorities

Metric	**Required Values**	**Verified Values**	**Units**
Weight of the Arm	<14	11.88	kg
Minimum Torque Output	2-10	2-20	Nm
Reach of Robotic Arm	>0.67	0.9	m
System Mass Distribution	0.209	0.132	kg/cm
Frequency of Motion	1	1	Hz

Cost Accounting and Cost Model

ORDER #	QTY	ITEM #	DESCRIPTION	VENDOR	LINK	UNIT COST	COST	
1	2	AK10-9 V2.0 KV100	Brushless DC Motor with driver board	Amazon	https://www.ama	$798.90	$1,597.80	
2	2	AK80-6 KV100	Brushless DC Motor with driver board	Robotshop	https://www.robo	$712.90		**Being ordered by sponsor
3	1	GL40 KV70	Gimbal Motor with encoder	Amazon	https://www.ama	$97.99	$97.99	
4	1	Aluminum Beam	1 ft Multipurpose 6061 Aluminum Rectangular Tube	McMaster-Carr	cmaster.com/6546	$40.47		**Refunded
5	1	Bearing - Crossed Roller	J1 Bearing: 80mm shaft High-Load Face-Mount Crossed-Roller Bearing	McMaster-Carr	ww.mcmaster.com/	$514.58	$514.58	
6	1	Ball Bearing	J2 Bearing: 60mm shaft Ball Bearing	McMaster-Carr	ww.mcmaster.com	$46.38	$46.38	
7	1	Ball Bearing	J3 Bearing: 55mm shaft Ball Bearing	McMaster-Carr	/w.mcmaster.com/	$36.12	$36.12	
8	1	Ball Bearing	J4: 35mm High-Load Face-Mount Crossed-Roller Bearing	McMaster-Carr	vw.mcmaster.com/	$217.66		**Refunded!
9	1	Ball Bearing	J5 Bearing: 20mm shaft Ball Bearing	McMaster-Carr	/w.mcmaster.com/	$13.12	$13.12	
10	3	94180A371	M6 x 1 mm Thread Size, 7.6 mm Installed Length	McMaster-Carr	w.mcmaster.com/9	$13.80	$41.40	
11	1	90128A332	M4 x 0.7 mm Thread, 15 mm Long	McMaster-Carr	w.mcmaster.com/9	$9.71	$9.71	
12	1	91290A049	Black Oxide, M2 x 0.4 mm Thread, 20 mm Long	McMaster-Carr	w.mcmaster.com/9	$15.21	$15.21	
13	1	91290A323	Black-Oxide, M6 x 1 mm Thread, 18 mm Long	McMaster-Carr	w.mcmaster.com/9	$19.58	$19.58	
14	1	91290A194	Black-Oxide, M5 x 0.8 mm Thread, 30 mm Long, Fully Threaded	McMaster-Carr	w.mcmaster.com/9	$5.74	$5.74	
15	1	91274A117	M4 x 0.7 mm Thread, 10 mm Long	McMaster-Carr	w.mcmaster.com/9	$5.28	$5.28	
16	2	94180A361	M5 x 0.8 mm Thread Size, 6.7 mm Installed Length	McMaster-Carr	w.mcmaster.com/9	$17.86	$35.72	
17	1	91290A248	Black-Oxide, M5 x 0.8 mm Thread, 22 mm Long	McMaster-Carr	w.mcmaster.com/9	$12.08	$12.08	
18	1	91290A316	Black-Oxide, M6 x 1 mm Thread, 10 mm Long	McMaster-Carr	w.mcmaster.com/9	$15.13	$15.13	
19	1	90128A212	M4 x 0.7 mm Thread, 10 mm Long	McMaster-Carr	w.mcmaster.com/9	$9.49	$9.49	
20	1	90128A208	M4 x 0.7 mm Thread, 6 mm Long	McMaster-Carr	w.mcmaster.com/9	$10.42	$10.42	
21	1	91290A222	Black-Oxide, M5 x 0.8 mm Thread, 8 mm Long	McMaster-Carr	w.mcmaster.com/9	$12.75	$12.75	
22	1	Heat Set Insert Tool Tips	Tips for Threaded inserts M2 M2.5 M3 M4 M5 M6	Amazon	x2-c7usoBtj7COnZ	$9.99		**Refunded
23	1	CRAFTSMAN Storage Organizer	30 Small Drawer Modular Storage System	Amazon	5OyBtYePXZkiW-L6	$20.98	$20.98	
24	1	Dog Kennel Outdoor	4'L x 4'W x 4.5'H	Amazon	&pf_rd_p=cd15227	$159.99	$159.99	
25	1	T-nut Slots	20PCS 4040 Series M6 T-Nut	Amazon	trusion-Profile-8m	$15.49	$15.49	
26	1	Black Flat Head Allen Head Joint Conecting Bolts	12-Pack M6 x 22mm	Amazon	AIJAQjc1XbLI3XC16	$7.99	$7.99	
27	4	CubeMars R-link V2.0	Debugging tool for AK Motors	RobotShop	r-link-v20-debuggin	$51.90	$207.60	
28	1	T-Key allen wrench set	8pc set Metric MM sizes 2-10	Amazon	5IUCQ?source=ps-s	$14.46	$14.46	
29	1	94180A351	M4 x 0.7 mm Thread Size, 4.7 mm Installed Length	McMaster-Carr	w.mcmaster.com/9	21.82	21.82	
30	1	94180A331	M3 x 0.5 mm Thread Size, 3.8 mm Installed Length	McMaster-Carr	w.mcmaster.com/9	20.44	20.44	
31	1	92095A177	Passivated 18-8 Stainless Steel, M3 x 0.50 mm Thread, 5mm Long	McMaster-Carr	w.mcmaster.com/9	7.39	7.39	
32	1	IVETTO Brand	7-port USB port	Amazon	-20&linkCode=df0	$19.99	$19.99	
33	1	Hanglife Store	Heat-set Threaded Inserts M2.5	Amazon	uk-axKA2OlZFuYaU	$8.99	$8.99	
34	1	4471N14	Face-mount Crossed-Roller Bearing	McMaster-Carr	ww.mcmaster.com/	$586.42	$586.42	
35	1	XT30 to Orings	14AWG Silicon Cable XT30 to O Ring Terminal Cable	Amazon	gH_CYY5mPL5t-F	$6.39	$6.39	
36	2	Dual Row Screw Terminal Strip	Terminal Block 6 Position 600V 100A	Amazon	-Dual-Rows-Term	$12.09	$24.18	
37	5	XT60 to Orings	12 AWG 1.5 M	Amazon	dib_tag=se&key	$13.27	$66.35	
38	2	Converter	XT30F to XT60M	Amazon	z_A2_3D-Q_iyVKI	$4.69	$9.38	
39	1	Battery Cable	6 AWG 5 feet	Amazon	p6TXN2NNAcO8I	$25.99	$25.99	
40	1	Cable Mesh	10 ft 1/2 inch	Amazon	xmb2k9-22lFzJzq	$7.63	$7.63	
41	4	Long USB Extension Cable	10 foot, Black	Amazon	21U?source=ps-s	$8.49	$33.96	
					Additional Customs Fee		514.41	
					Shipping (McMaster)		51.28	
						TOTAL	$4,329.63	

Cost Accounting and Cost Model

Univeristy/Sponsor Inventory							
Part	**Part Number**	**Vendor**	**Cost each**	**Qty**	**Total Cost**	**Notes**	**Restrictions?**
Power Supply	9115B/08AK4948	Newark	$2,550.00	1	$2,550.00	80V, 60A	
4040 T-slot Aluminum Extrusion	350 millimeter	FEDC	$9.75	2	$19.50		
3D Printed Parts	Printed using PLA	RPS	N/A	N/A			
M6 x 20mm	N/A	RPS	$9.99	1	$9.99		
Soldering Iron	Used to insert heatset inserts into PLA parts	RPS	$16.99	1	$16.99		
M3 x 4mm	N/A	RPS	$6.99	1	$6.99		
M4 x 8mm	N/A	RPS	$11.89	1	$11.89		
M6 Washers	N/A	RPS	$4.99	1	$4.99		
M6 Hex Nuts	N/A	RPS	$9.99	1	$9.99		
M2.5 x 6mm	N/A	RPS	$7.29	1	$7.29		
M2.5 x 5mm	N/A	RPS	$7.19	1	$7.19		
M4 washers	N/A	RPS	$4.99	1	$4.99		
M4 Hex Nuts	N/A	RPS	$9.99	1	$9.99		
				Customs Fee	$514.41		
				Shipping	$51.28		
				Total	$8,376.05		

Broader Impact of Design

I. Lifecycle Design
II. Intellectual Property (IP)
III. Liability Considerations
IV. Ethical Considerations/Concerns

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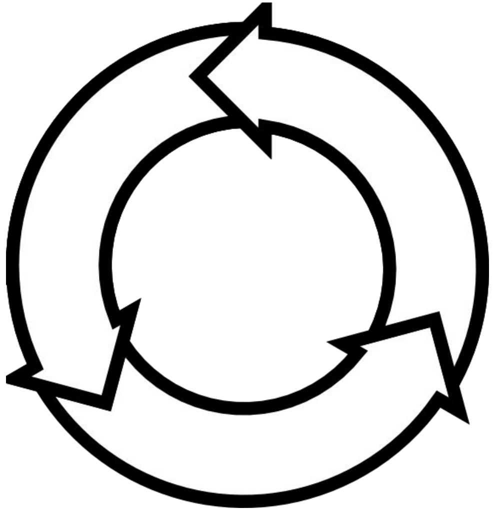
Lifecycle Design

Motors:
- CubeMars brushless DC motors chosen for low maintenance
- Routine checks include visual/electrical inspections, cleaning, and load/environment monitoring
- Maintained within –20 °C to 65 °C; wire mesh used to secure connections

Structure & Materials:
- Lightweight design prevents motor overload
- PLA used for 3D-printed joints
    - lightweight with high print accuracy but limited durability

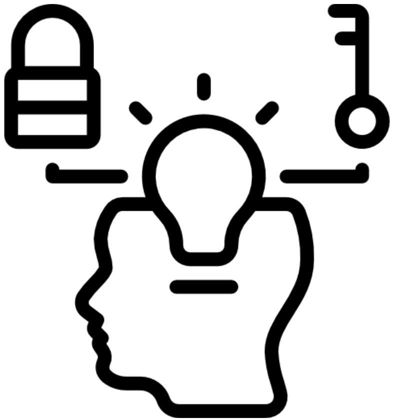
Modular Design:
- Each joint is independently serviceable for easy motor replacement
- Damaged parts can be reprinted using open-source design files

Sustainability:
- PLA is industrially compostable
- E-waste should be recycled via certified programs



Intellectual Property (IP)

- No IP involved (patents, trademarks, copyrights, or trade secrets)
- Design is original but not novel or non-obvious enough for protection
- Based on industrial designs using commercial parts
- Follows standard engineering practices; no unique algorithms or systems
- Created for educational use; intended for open academic sharing
- Project files are publicly available on GitHub for replication and learning



Liability Considerations

Prototype Liability Considerations

- Key risks: pinch points, unexpected motion, mechanical failure
- Mitigations:
  - Safety cage installed for physical protection during testing
  - Motor torque and speed limited to reduce injury risk
  - No formal product liability concerns due to educational use at a national laboratory

Production Liability Considerations

- Intended use: remote hazardous waste cleanup at a national laboratory
- Must comply with federal and state safety regulations (OSHA, DOE)
- Potential liabilities:
  - Injury to personnel
  - Damage to equipment

Ethical Considerations/Concerns

User Safety:

- Treated as the top ethical priority
- Safety protocols included limiting speed/torque and using a safety cage
- Physical barriers ensured safe prototyping and testing environments
- Emphasis on predictable, non-hazardous operation for manual use

Transparency & Honesty:

- Performance reporting prioritized throughout development
- Regular communication maintained with sponsor via emails and meetings
- Weekly updates provided to studio professor during each session

Summary

I. Work Breakdown Structure
II. Final Gantt Chart and Project Plan
III. Technology Development
IV. Limitations
V. Future Work

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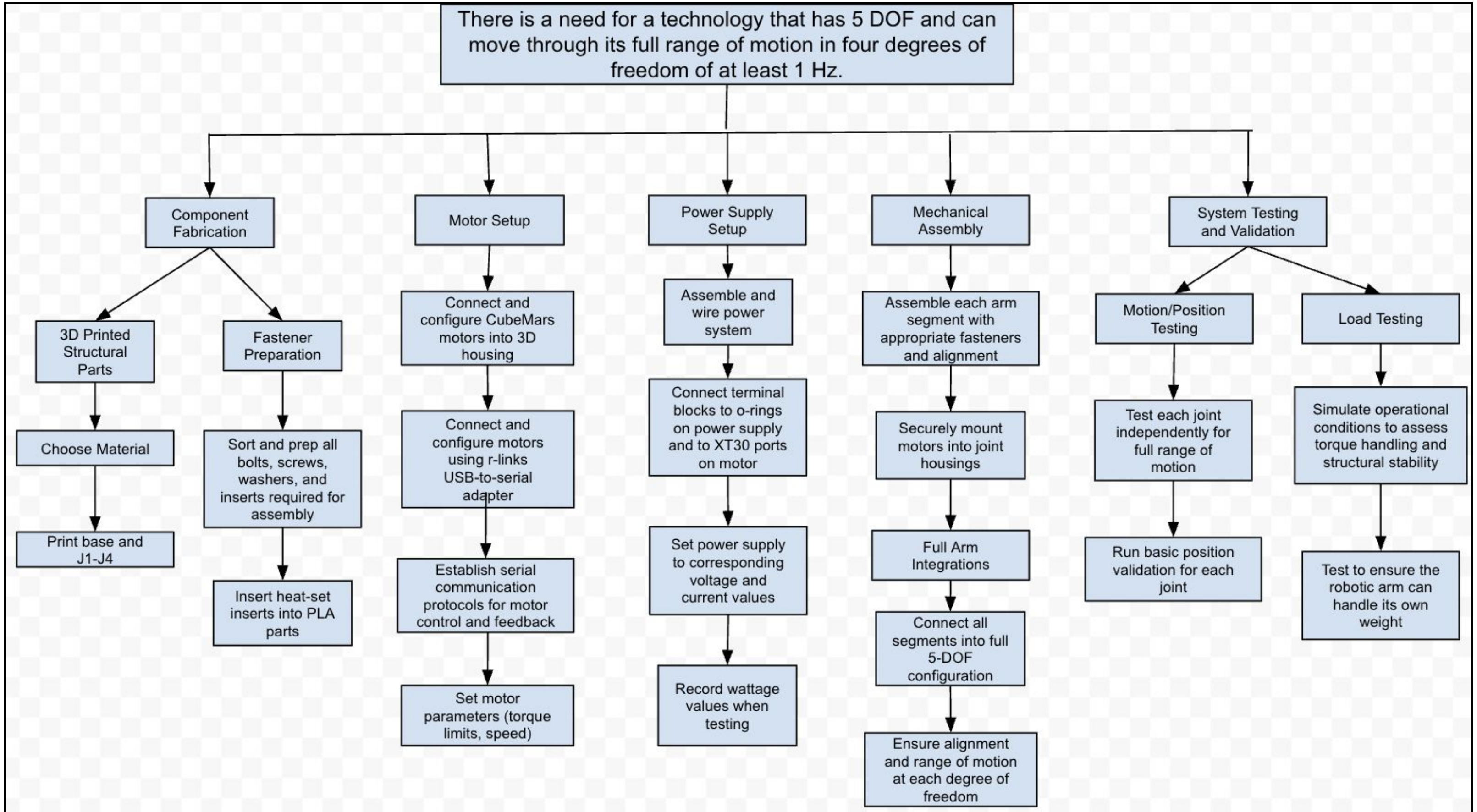
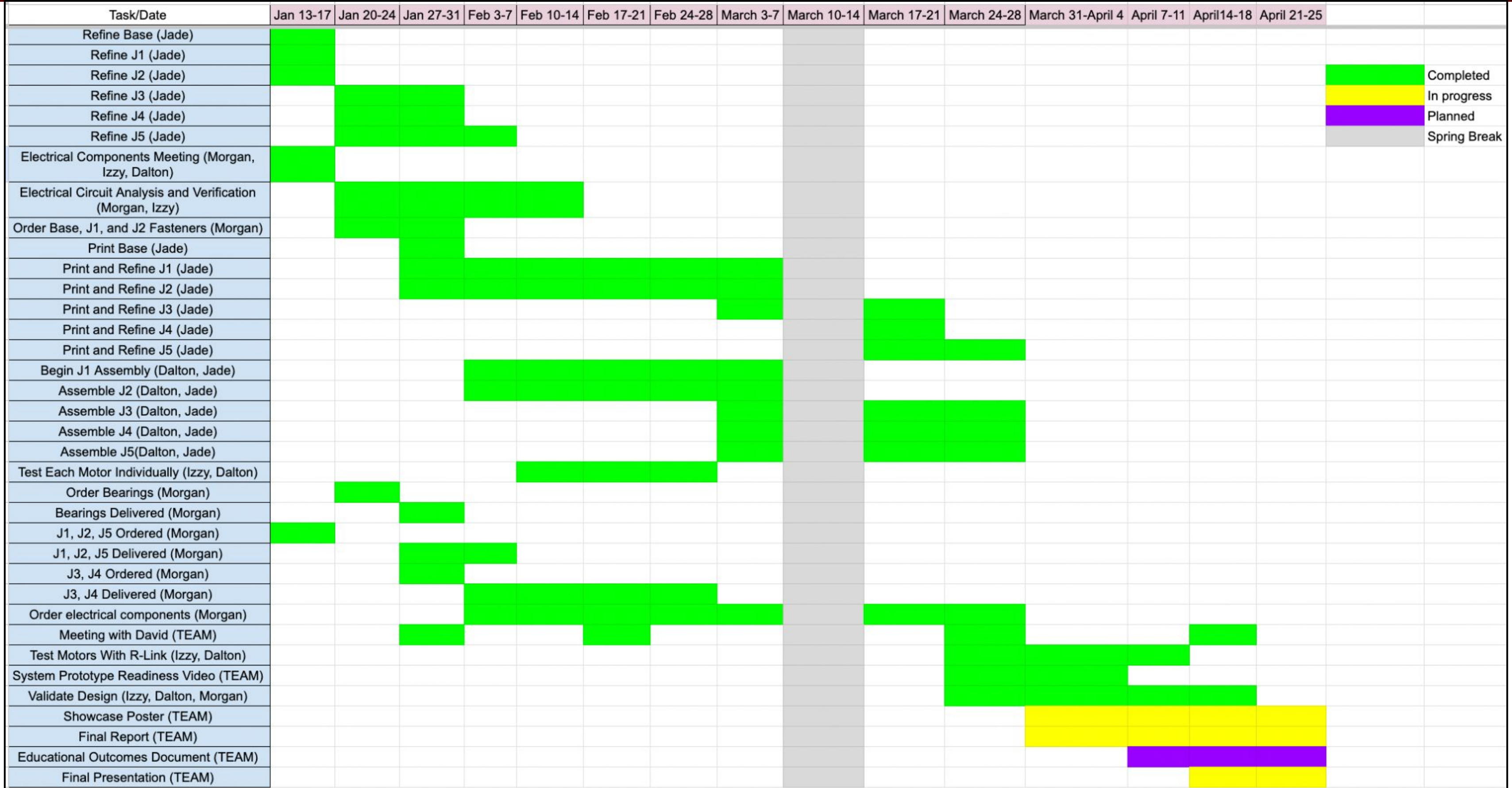
Work Breakdown Structure (WBS)



Final Gantt Chart and Project Plan



Technology Development

Challenge Identified:

- Unable to control multiple motors at the same time

Required Knowledge for Integration:

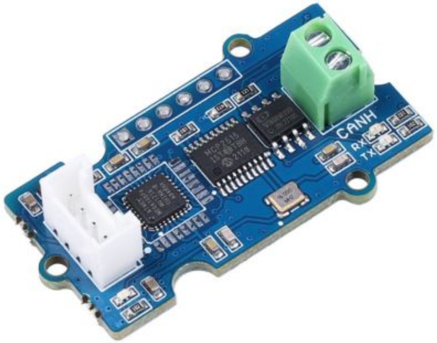
- Understanding of motion control systems and servo driver configuration
- Familiarity with feedback loops and communication protocols (e.g., CAN bus)

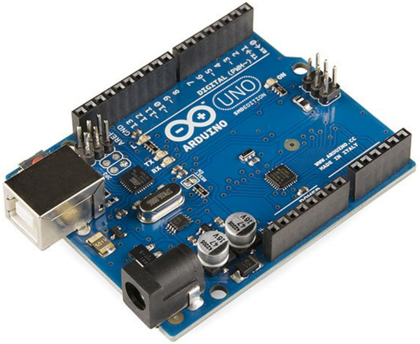
CAN Bus & Arduino for Multi-Motor Control:

- CAN bus enables communication between Arduino and multiple motors using unique CAN IDs
- Requires a CAN transceiver like the MCP2515 module
- Arduino sends commands using libraries like MCP_CAN_lib to control speed/position

Future Implementation:

- Enables real-time, synchronized, and scalable motor control for complex systems





Technology Development

Challenge Identified:

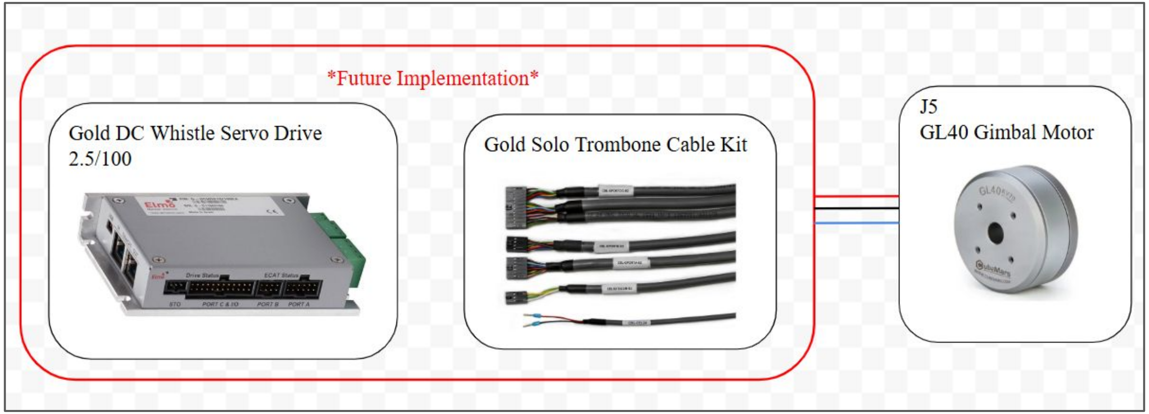
- GL40 Gimbal Motor incompatibility with the R-link device
- Resulted in inability to operate the fifth joint of the robotic arm

Recommended Components (by Elmo Motion Control):

  - G-DCWHI2.5/100SESQ – High-performance servo driver
  - CBL-GDCWHIKIT02 – Wiring kit designed for the servo driver

Future Implementation:

- Allows future teams to power and control the gimbal motor
- Ensures full functionality of the robotic arm's fifth joint



Technology Development

Challenge Identified:

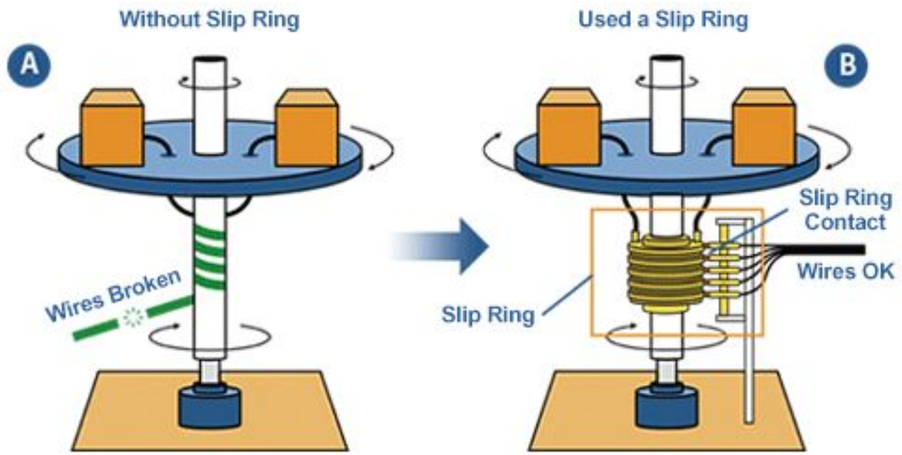
- Wiring limited 360° rotation, risking entanglement and interrupting power to brushless DC motors

Resolution Steps:

- Identified need for a split-ring to maintain continuous electrical connection during rotation
- Ensured stable power and signal integrity for smooth, unrestricted motion

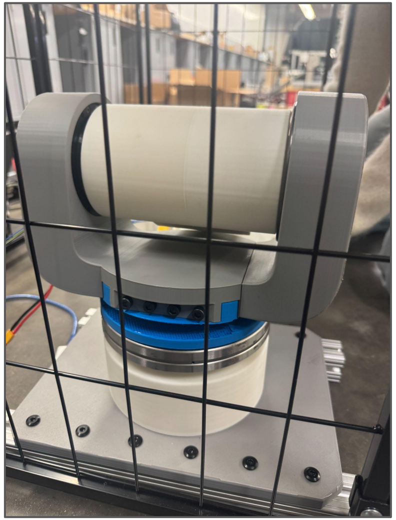
Future Implementation:

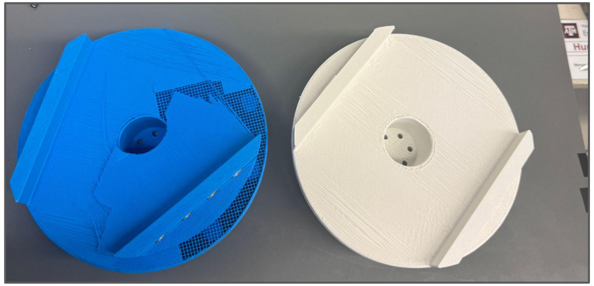
- Custom design a split ring to fit the robotic arm's specs
- Integrate into future builds to enable full motion and protect wiring



Limitations: Mechanical and Structural

- Single-Joint Control only – current software allows only one motor to move at a time, preventing smooth, multi-joint coordination
- Limited durability – Due to use of PLA components, the arm is not suitable for high-radiation or high-temperature environments. The PLA might struggle under high torque loads as well.
- No integrated end-effector
- Structural performance not yet verified under prolonged cyclic loading or high-vibration conditions



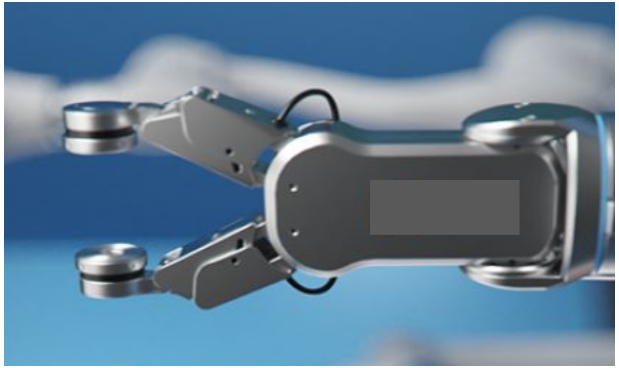


Limitations: Control and Wiring

- Limited Force Control – Operation is restricted to MIT mode for safety, full capabilities in servo mode remain untested due to risk
- External Cable Routing/Cable Management – wiring constraints joint motion, reduces workspace, and increases the risk of entanglement or damage
- No gravity compensation – arm lacks real time torque adjustment for gravity, extensive manual tuning is required for different movements and loads

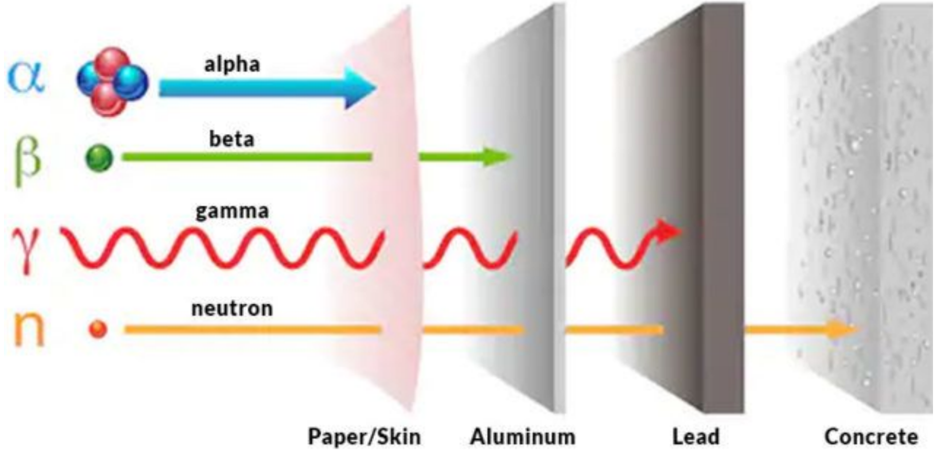
Future Work: Control and Functionality

- Utilize multi-joint control algorithms to enable coordinated movement across all 5 degrees-of-freedom
- Incorporate sensors for feedback-driven control
- Refine control system architecture to allow for real-time user interface and potential joystick control
- Explore safe operation in servo mode by designing advanced control algorithms
- Integrate closed-loop feedback for smoother, more adaptive control during tasks



Future Work: Mechanical and Structural

- Upgrade structural components to radiation resistant materials
- Conduct durability and fatigue testing to assess performance under prolonged use
- Implement real-time gravity compensation based on arm pose and motor feedback
- Redesign for internal cable routing to expand range of motion
- Design and integrate a task specific end-effector, such as a cleaning brush or scraping tool



Assembly Manual

- Assembly Manual complete
- ~60 pages long (lots of figures, cover pages, etc…)

Step 6: J5 Assembly Instructions

Purpose: This section details the assembly of the J5 housing, including the motor, bearing, and attachment to J4 and the Forearm.

Parts List:

- Forearm (Quantity: 1)
- J5 Motor Holder (Quantity: 1)
- J5 Bearing Holder (Quantity: 1)
- J5 Cylinder (Quantity: 1)
- J5 Cylinder Cap (Quantity: 1)
- J5 Motor (GL40) (Quantity: 1)
- J5 Bearing (5972K105)

Hardware:

- 4 M2.5x5 mm screws
- 4 M2.5 heat set inserts
- 8 M3x5 mm screws
- 14 M4x10 mm screws
- 8 M4 washers
- 8 M4 nuts

Tools Required:

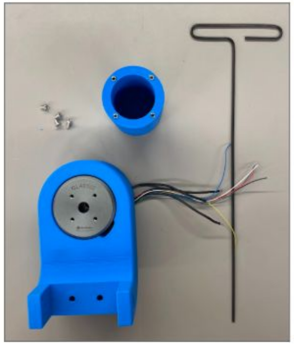
- Soldering Iron
- M2.5 Soldering Iron Tip
- M2.5 Allen Wrench
- Long M3 Allen Wrench
- M4 Allen Wrench

1. Heat Set Insert Installation:

- **Caution:** Work in a well-ventilated area. PLA can release fumes when heated. THE PLA PARTS WILL BE HOT TO THE TOUCH (for about 5-10 minutes) BE CAREFUL.
- Before turning the soldering iron, ensure you have the correct size soldering tip to match the heat set insert size.
- Using the soldering iron heated to approximately 200°F (start lower and adjust as needed), carefully install four **M2.5 heat set inserts** into the designated holes near the opening of the J5 Cylinder. Use Needle Nose pliers to assist holding the Heat set insert in place.

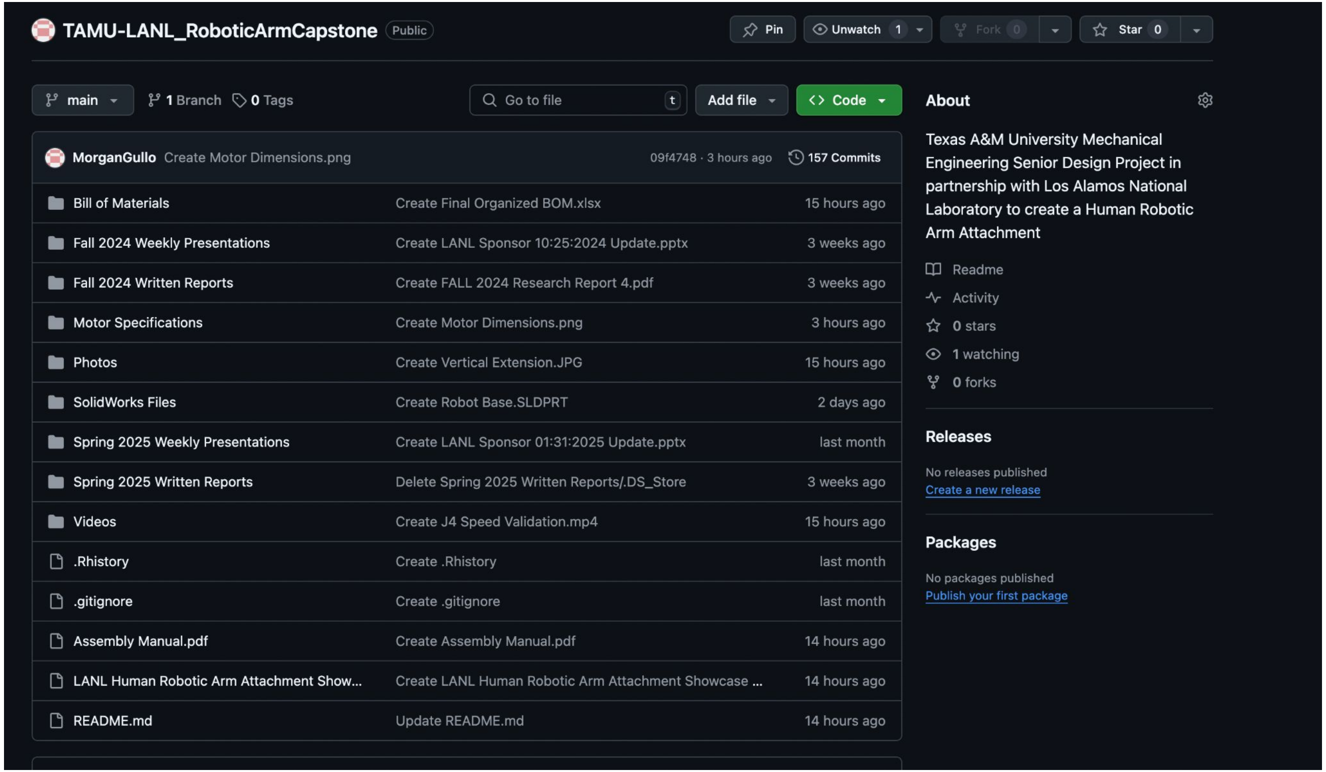
5. J5 Cylinder to J5 Motor

- Prepare the J5 Motor Holder (with J5 motor intact), 4 M3x5 mm screws, and a long M2.5 allen wrench



- There will be 4 holes in the cylinder that will match with the front face of the J5 Motor
- Place the J5 Cylinder on the J5 Motor Face
- Use 4 M3x5 mm screws and fasten the cylinder onto the face of this motor.

GitHub


TAMU-LANL_RoboticArmCapstone
Public
Pin
Unwatch 1
Fork 0
Star 0
main
1 Branch
0 Tags
Go to file
t
Add file
Code
MorganGullo Create Motor Dimensions.png
09f4748 · 3 hours ago
157 Commits
Bill of Materials | Create Final Organized BOM.xlsx | 15 hours ago
Fall 2024 Weekly Presentations | Create LANL Sponsor 10:25:2024 Update.pptx | 3 weeks ago
Fall 2024 Written Reports | Create FALL 2024 Research Report 4.pdf | 3 weeks ago
Motor Specifications | Create Motor Dimensions.png | 3 hours ago
Photos | Create Vertical Extension.JPG | 15 hours ago
SolidWorks Files | Create Robot Base.SLDPRT | 2 days ago
Spring 2025 Weekly Presentations | Create LANL Sponsor 01:31:2025 Update.pptx | last month
Spring 2025 Written Reports | Delete Spring 2025 Written Reports/.DS_Store | 3 weeks ago
Videos | Create J4 Speed Validation.mp4 | 15 hours ago
.Rhistory | Create .Rhistory | last month
.gitignore | Create .gitignore | last month
Assembly Manual.pdf | Create Assembly Manual.pdf | 14 hours ago
LANL Human Robotic Arm Attachment Show... | Create LANL Human Robotic Arm Attachment Showcase ... | 14 hours ago
README.md | Update README.md | 14 hours ago
About
Texas A&M University Mechanical Engineering Senior Design Project in partnership with Los Alamos National Laboratory to create a Human Robotic Arm Attachment
Readme
Activity
0 stars
1 watching
0 forks
Releases
No releases published
Create a new release
Packages
No packages published
Publish your first package

Acknowledgements

- Dr. David Mascarenas – Project sponsor; provided key guidance and support throughout
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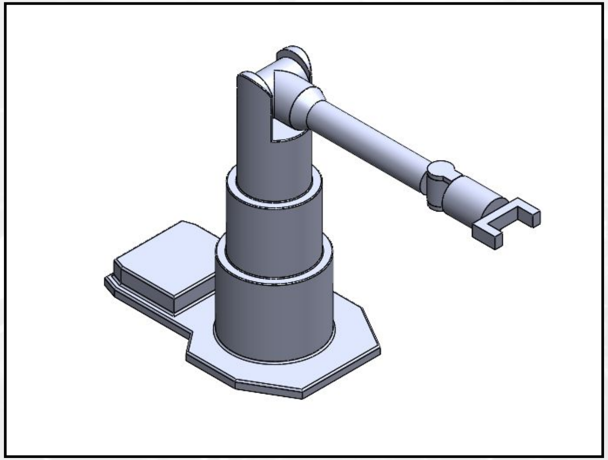
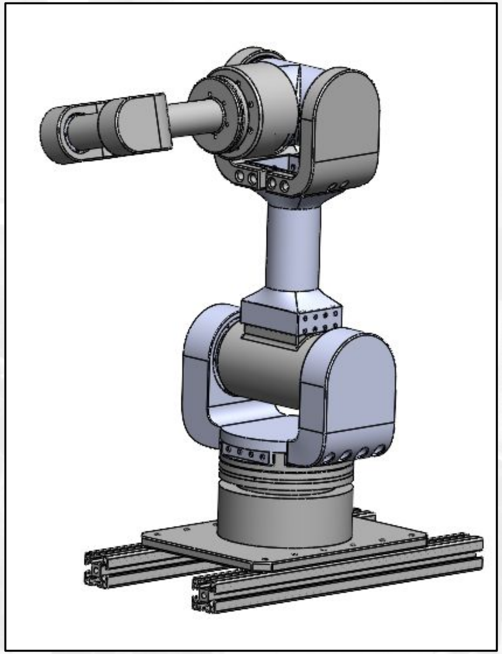
Thank You!

1st Design



Final Design



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