**MEEN 402 INTERMEDIATE DESIGN; SECTION 502**
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# MIDTERM REPORT


TEXAS A&M UNIVERSITY
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# Human Robotic Arm

**Sponsor: Los Alamos National Laboratory**

**"On my honor, as an Aggie, I have neither given nor received unauthorized aid on this academic work."**

**Signed: Izzy Baumler, Dalton Boeckmann, Morgan Gullo, Jade Waldron**

# Executive Summary

Students from Texas A&M University will design, with the help of Dr. David Mascarenas from Los Alamos National Laboratory, a robotic arm attachment for solving a crucial cleaning need within nuclear waste facilities. This project aims to enhance remote hazardous material handling operations by affixing a 5 DoF robotic arm to the body of a quadruped Boston Dynamics Spot robot. These robotic arms attached to Spot robots will be built and designed to clean radioactive waste residues to minimize contamination risks without direct human intervention.

The project arose from accessibility limitations and safety problems common in nuclear waste facilities identified during discussions with professionals at the Los Alamos Research Laboratory. The team has successfully completed one semester of planning, sketching, and outlining all the necessary components needed to build this robot. For the past 2 months, the team transitioned into purchasing, fabricating, and manufacturing their plans. This robot now receives inputs from a computer, with a primary focus on achieving a functional frequency of at least 1 Hz to ensure reliable performance under various conditions.

As a guide to the development of the solution, the team began identifying the customer needs with an integrated approach: preliminary research, expert interviews with Savannah River National Laboratory, and a Supplemental Design Survey. This holistic approach helped identify the critical needs for the arm, such as maneuverability, lightweight construction, and rapid response. Moreover, the survey showed concerns about stability, weight, and balance, especially when integrated with a quadruped robot, which allowed the team to focus on keeping the center of gravity low. While precision was important, speed and versatility became the main focus, reflecting both the operational environment and customer expectations. These were tabulated in **Table E1**, summarizing the key customer needs and their respective importance scores.

**Table E1:** The customer needs table presents the customer needs identified from literature sources and interviews.

| # | 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 |

The team has developed a robotic arm consisting of five main subassemblies, each corresponding to a motorized joint. The robotic arm is designed for enhanced functionality and precision, incorporating advanced materials, fastening techniques, and electrical components for optimal performance. The final assembly, depicted in **Figure E1**, integrates all subassemblies along with the base and aluminum extrusions to ensure stability and structural integrity.

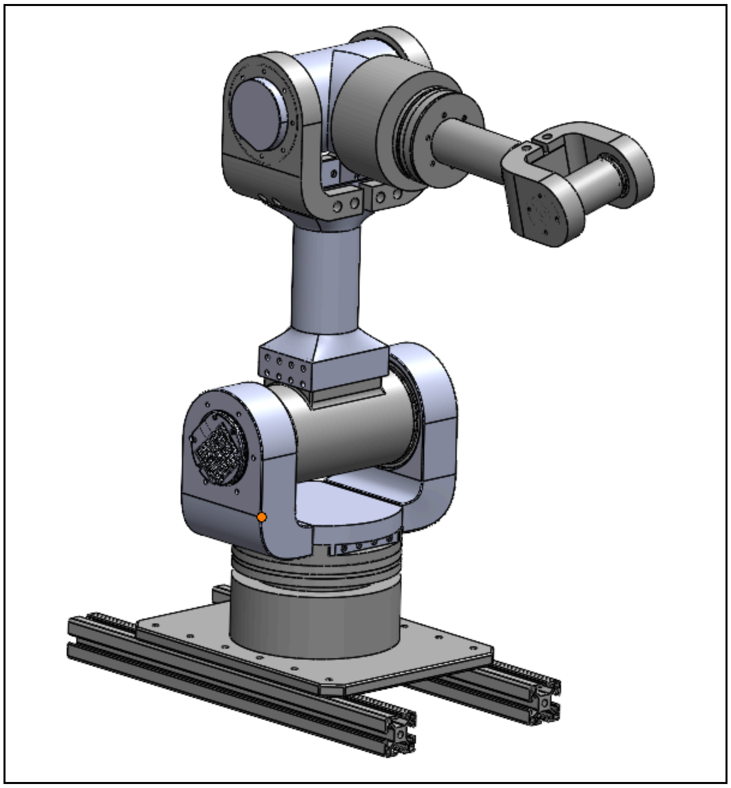

**Figure E1**: Final CAD Assembly

The J1 subassembly is primarily responsible for supporting the entire weight of the robotic arm. It comprises five key components: the J1 Motor Holder, J1 Mushroom Cap, J1 Motor Cover, J1 Motor, and J1 Cross Roller Bearing. The cross-roller bearing minimizes friction and distributes torque loads, ensuring longevity and efficiency. The J1 Mushroom Cap interfaces J1 with J2 via heat-set inserts for secure assembly. Clearance holes (M4–M6) simplify alignment, reducing stress on fasteners and streamlining assembly. The J2 subassembly enables vertical translational movement, increasing the arm's operational reach. This assembly consists of the J2 Motor Holder, J2 Motor, J2 Ball Bearing, J2 Bearing Holder, and the J2 Cylinder. The motor and bearing are positioned on opposite sides of the cylinder, allowing efficient force distribution and motion. J3 emulates the movement of a human elbow, providing an additional up-and-down motion. Its design mirrors that of J2 but with a reduced size for weight optimization. The J3 assembly consists of the Bicep, J3 Motor Holder, J3 Motor, J3 Ball Bearing, J3 Bearing Holder, and the J3 Cylinder. By incorporating this degree of freedom, J3 enhances dexterity and overall arm functionality. J4 introduces rotational movement similar to a human forearm. It consists of the J4 Motor Holder, J4 Motor Cover, J4 Cross Roller Bearing, J4 Mushroom Cap, and J4 Motor. This design is functionally similar to J1 but interfaces with J3 instead of the base, maintaining consistency in torque distribution and movement control. Finally, the J5 subassembly enables wrist-like movement, crucial for precise manipulation. It comprises the Forearm, J5 Motor Holder, J5 Bearing Holder, J5 Cylinder, J5 Cylinder Cap, J5 Motor, and J5 Bearing. The J5 joint ensures fine control and flexibility, enabling the arm to grasp and interact with objects accurately.

For initial prototyping, PLA was selected due to its affordability, ease of printing, and dimensional accuracy. However, if budget allows, PETG will be utilized due to its superior strength, flexibility, and thermal resistance. This transition ensures durability and resilience under operational loads. Fastener selection was guided by motor sizing constraints, cost, and vibrational forces. Socket head cap screws (M3–M6) were chosen due to their compact head design, high tensile strength (~170,000 psi), and ability to withstand torque loads without loosening. Heat-set inserts in PLA components prevent dynamic loosening, ensuring long-term reliability. The control system employs an MCP2515 CAN Bus and an Arduino Uno allowing centralized motor control. The system architecture, as depicted in **Figure E2**, enables real-time multi-device communication. A wiring plan details the pin connections between the CAN Bus and Arduino Uno, ensuring accurate signal transmission. A motor setup was used to illustrate the final control configuration, which is programmed using the Arduino IDE with a C-based language for precise motion execution.

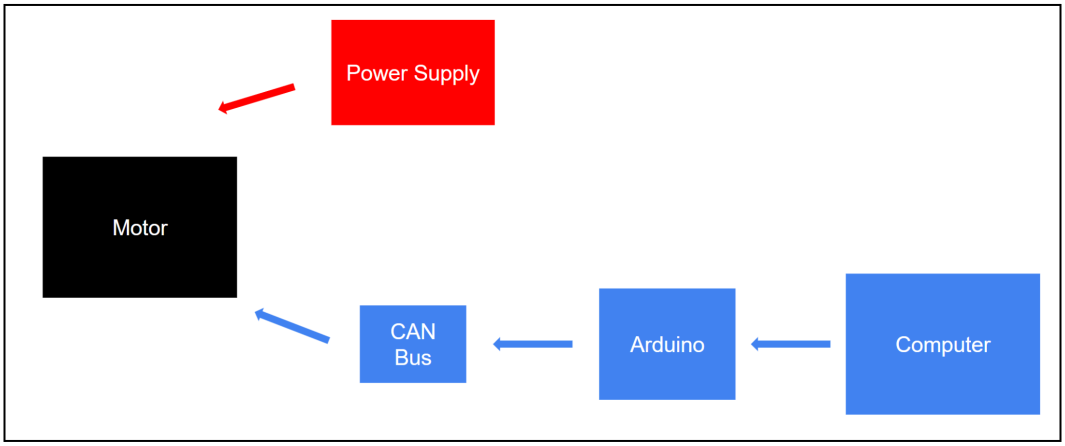


**Figure E2**: Communication Order for Controls System

The design, development, and validation of the robotic arm have been an overlapping process encompassing extensive engineering challenges, iterative design improvements, and rigorous testing protocols. This document outlines the key aspects of the design analysis, highlighting logistical hurdles, manufacturing constraints, design validation, risk assessment, and financial considerations.

The transition from conceptualization to fabrication revealed numerous logistical and design challenges. Key manufacturing difficulties included precise tolerance adjustments for 3D-printed PLA components, infill percentage modifications to ensure structural integrity, and redesigns to accommodate fastener clearances. Motor control was another significant hurdle, requiring extensive troubleshooting of the Arduino to CAN Bus interface. Initial testing was conducted using an R-link to an Upper Computer connection provided by Cube Mars, providing successful individual motor actuation results.

Budgeting constraints and international trade policies also presented financial challenges. The team faced an unplanned $500 tariff fee on motor imports, necessitating adjustments in purchasing strategies. Support from LANL allowed the team to acquire essential components, enabling them to reallocate funds toward other critical materials and safety enhancements.

A systematic evaluation of the design ensured functionality, manufacturability, and compliance with engineering principles. The assessment covered: Functionality & Efficiency, Material & Geometry Considerations, Safety & Reliability, and Energy & Motion Control. The team conducted a quantitative review of each aspect, identifying unresolved design aspects and assigning corrective measures with set deadlines to maintain project momentum. To mitigate potential system failures, the team employed Failure Modes, Effects, and Criticality Analysis (FMECA) to evaluate weak points in the robotic arm's design. The most critical failure modes were identified and rated based on severity and likelihood, guiding subsequent design improvements. A Fault Tree Analysis (FTA) further refined the risk assessment by breaking down high-level system failures into specific root causes. This methodology enabled the team to proactively address probable faults and implement robust mitigation strategies.

Validation efforts have centered around prototyping, assembly, and motor testing. The primary focus has been ensuring: joint articulation and performance benchmarks, Structural integrity under operational loads is maintained, and motor control system integration functions reliably. Preliminary results indicate successful communication between the control system and individual motors. Adjustments in assembly tolerances and iterative redesigns have enhanced precision and reliability. Ongoing troubleshooting continues to refine the Arduino-CAN bus interface for full-system integration.

The team's initial $5,000 budget has been managed carefully, with approximately $3,500 spent, primarily on motors and bearings. The unexpected tariff expenses prompted strategic reallocation of funds, and sponsorship support helped secure key components without exceeding budgetary limits. Resources from the FEDC and the Mechanical Engineering department further reduced costs by providing access to 3D printing and machining facilities. The final cost projection remains under $4,000, with additional planned purchases for electrical components and potential reprints in more durable materials.

Finally, the team has committed to delivering the following final outputs, as specified in the MEEN 402 senior design project success agreement: Fully assembled 5-DOF robotic arm prototype, SolidWorks CAD model of the fully assembled robotic arm, Base and J1-J5 individual SolidWorks CAD assemblies and engineering drawings, a circuit block diagram of the motor electrical design, an assembly instruction manual, a final report detailing work performed in MEEN 402, and a final presentation summarizing project outcomes. These deliverables encompass both hardware and documentation, ensuring a comprehensive project handoff to future stakeholders.

The validation phase follows a structured timeline to ensure functionality and reliability:

- Construction & Fabrication (Weeks 1-3): 3D printing, motor sourcing, and power supply acquisition.
- Assembly & Integration (Weeks 4-6): Installation of motors, heat-set inserts, and bearings, as well as power and control system integration.
- Motor Programming & Control Development (Weeks 7-11): Individual motor testing, controller programming, and implementation of safety mechanisms such as a kill switch.
- Testing & Calibration (Weeks 12-13): Joint movement testing, error debugging, and system-wide safety checks.
- Final Validation & Adjustments (Weeks 14-15): Comprehensive performance testing to ensure speed, weight, reach, torque, and accuracy meet predefined specifications.

The corresponding schedule that the team has followed can be seen in **Figure E3**.

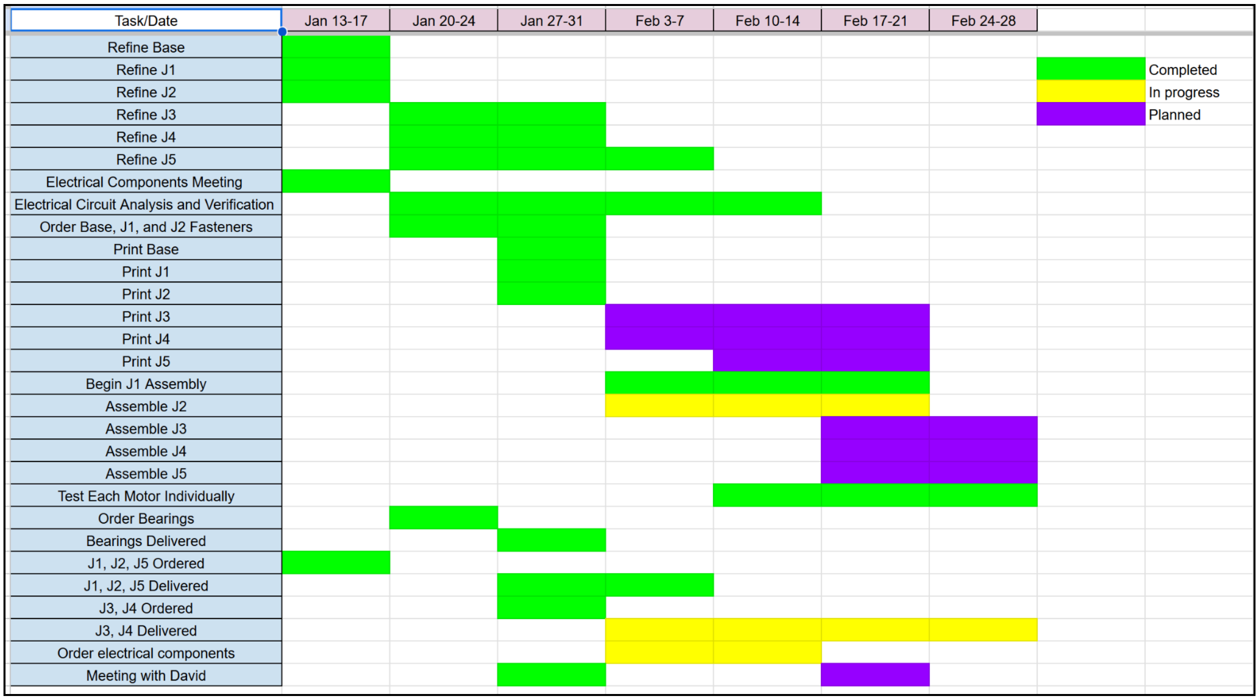


**Figure E3**: Capstone progress Google sheet

Several risks have been identified and addressed to enhance the system's durability and operational safety. To mitigate these risks, several plans have been put forth to help reduce these risks. Mechanical wear and structural integrity concerns are addressed through the selection of high-strength materials, with PLA used for the prototype and PETG for production. Additionally, increased infill density is applied to high-stress components to enhance durability. Software bugs and control stability issues are mitigated through rigorous pre-assembly motor testing and thorough debugging of the control system. Safety and human interaction risks are managed by implementing an emergency stop mechanism and a protective cage, which prevents unintended access and enhances overall operational safety.

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# Glossary Table

| Term | Definition |
|---|---|
| LANL | Los Alamos National Laboratory |
| SNPS | Solution Neutral Problem Statement |
| DOE | Department of Energy |
| DoF | Degrees of Freedom |
| PLA | Polylactic Acid |
| PETG | Polyethylene Terephthalate Glycol |
| FMECA | Failure modes, effects, and criticality analysis |
| FTA | Fault Tree Analysis |
| CAD | Computer-Aided Design |

# 1. Introduction and Problem Definition

Over its 45 years of plutonium production, the Hanford Site in Washington State has accumulated over 56 million gallons of mixed hazardous and radioactive waste. The waste was initially stored in tanks designed to last 25 years; however, most of these tanks have far exceeded their intended lifespans, with about 68 tanks reaching critical conditions. The state of these tanks poses an increasing threat to both local populations and infrastructure. Through the partnership with Los Alamos National Laboratory (LANL) and Texas A&M, they have engaged a senior design team to design and fabricate a solution for this problem. The senior design team consists of four Mechanical Engineering students; Dalton Boeckmann, Isabelle Baumler, Morgan Gullo, and Jade Waldron, and is overseen by Dr. David Dennis Lee Mascarenas from LANL. In this paper, the team presents the design process for a 5-DoF robotic arm attachment for a quadruped robot to assist with cleaning operations inside nuclear waste tanks.

The design team in collaboration with engineers from Los Alamos National Laboratory (LANL) and environmental experts, identified various challenges of removing solidified radioactive waste at the Hanford Site. LANL professionals emphasized the risks posed by waste that has crystallized over decades, highlighting that while the Department of Energy (DOE) has focused on liquid waste removal, there haven't been many advances in solidified waste removal.

Some key obstacles were highlighted including the tanks' one-foot-diameter openings, which limit equipment access, the high radioactivity requiring remotely operated devices that often underperform, and the need for the robotic arm to have an efficient operational speed and human-like mobility.

To address these challenges, the project team identified the need for a 5 Degree of Freedom (DoF) robotic arm that could be mounted on a quadruped robot for effective nuclear waste tank cleaning. This design hopes to enable human-like mobility and operational speed while performing cleaning operations to reduce environmental risks and stabilize the Hanford Site.

Current robotic solutions proposed for hazardous waste management cannot meet the demands of a confined highly radioactive environment like the Hanford Site. Many systems lack the required mobility, flexibility, and reliability; hence, mechanical failure in high-level radiation, uneven surfaces, and restricted access points is experienced in many of them [3, 4]. This emphasizes the need to have a more robust solution.

While there is progress in robotics relating to hazardous environments, many robots are designed for efficient mobility or manipulation, but rarely both. According to research, fixed robotic arms allow good manipulation but offer very slow speeds, while faster systems usually have coarse control and cannot accomplish tasks like breaking up solidified wastes. Therefore, these limitations impede efficient cleaning and waste removal processes from the storage tanks within the Hanford Site [2,6]. However, access is further constrained by having only one-foot-diameter tanks, which restricts equipment that can be deployed [5]. Furthermore, high levels of radiation make operations of remote-operated equipment a necessity to minimize human exposure; unfortunately, many systems fail under these extreme conditions and cannot complete the operations, further increasing environmental risks [4,5].

In response, the project team proposes a 5-degree-of-freedom robotic arm mounted on a quadruped robot. The quadruped robot provides stability on uneven surfaces, while the 5-DoF arm will manage waste in those areas where cleaning is necessary. While promising research into similar systems has been conducted, no solution to date has fully addressed the unique challenges presented by the tanks at the Hanford Site [6,3]. This project seeks to address these efforts by creating a dynamic, yet robust robotic system able to perform operations rapidly, while ensuring mobility, and safety during waste removal operations.

## 1.1. Needs Analysis

### *1.1.1. Solution Neutral Problem Statement*

The Solution Neutral Problem Statement (SNPS) can be seen as outlined in **Table 1** and was developed based on comprehensive research along with the defined functionality of the project.

The SNPS serves to define abstract and unbiased criteria for an innovative and successful design. As the scope of the project was limited and/or different custom needs were expressed, the SNPS was frequently revised and updated.

**Table 1:** The SNPS identifies the basis of the problem the LANL Project Team will address

| | |
|---|---|
| **SNPS** | There is a need for a technology that has 5 DoF and can move through its full range of motion in each degree of freedom around 1 Hz. |
| **Customers** | Department of Energy, National Research Laboratories |

### *1.1.2. Mission Statement*

Through the development of the SNPS, the team arrived at a mission statement that helped clarify the LANL project team's design goal to meet the needs of the design team and customers. The mission statement can be seen clearly defined in **Table 2**. The mission statement outlines that the LANL project team will design and prototype a 5 DoF robotic arm that is optimized through the design selection of material, robotic actuation for arm movement and control, and the semi-autonomous control system. Considering limited resources and timelines, the team has decided to focus on the design of the mechanical aspects of the robotic arm, focusing specifically on optimizing the speed and dynamic capabilities of the manipulator.

**Table 2:** Outline of the LANL Teams Mission Statement with key influencing Factors

| **Mission Statement: LANL Power Tool Arm Attachment for a Quadruped Spot Robot** | |
|---|---|
| **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<br>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 |

*1.1.3. Technical Questioning Results*

In MEEN 401, the team underwent an extensive technical questioning process to better understand the functionality of the LANL project, along with the necessary engineering tasks to meet the project deliverables effectively. The process of the technical questioning helped refine both the SNPS and the Mission Statement for the LANL Team. The complete technical questioning document can be seen in **Appendix A**. One major takeaway was the implementation of different dynamic actuators that could enhance the dynamic behavior of the robotic arm. From this the group will need to develop different designs that implement various actuation processes, improving the robot's operational speed. These design choices may be limited due to cost and or weight and their effect on the payload of the robotic arm. Overall the team was able to identify the most important design parameters to be robotic actuation, the material of the robotic arm, and the semi-autonomous behavior. This process enhanced and offered support for the SNPS, clarifying and limiting the team's direction for innovative designs.

*1.1.4. Customer Needs Table*

Last Semester, the team used a variety of methods to retrieve, select, and rank customer needs. The team determined initial needs and importance values from preliminary research. The group then contacted two researchers from Savannah River National Laboratory to determine direct needs. The group used a Customer Needs Interview form to determine needs and important values from these meetings. A completed sample of this form is presented in **Appendix B**. The group also created a Supplemental Design Survey to collect additional perspectives on 5-DoF arm capabilities. A sample of this survey is presented in **Appendix C.** Respondents compared the importance of identified needs and submitted additional comments. The group determined importance scores for the needs based on a holistic evaluation of preliminary research, Customer Needs Interview comments, and Supplemental Design Survey responses.

**Table 3** presents the customer needs and importance values identified from research and interviews. The most critical needs for the robotic arm design were its ability to have dexterity similar to a human arm, lightweight construction, and fast maneuvering. For robotic arms in the industry, the needs are very specific to the purpose and functionality of the product. For our human arm, interview respondents and our sponsor emphasized the importance of a highly maneuverable/fast arm. Additionally, precise/accurate control, versatility, durability, and stability were seen as important as well. Respondents also seemed less concerned about the arm being semi-autonomous.

**Table 3:** The customer needs table presents the customer needs identified from literature sources and interviews.

| # | **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 |

Feedback from the customer survey raised valid concerns regarding the needs that were presented in **Table 3**. The primary concerns highlighted by the survey responses and feedback include the need for stability, especially considering the arm's weight and positioning on the quadruped robot. There is a risk of tipping over if the arm is too heavy or experiences sudden movements, so maintaining a low center of gravity and optimizing balance is essential. According to our sponsor, the arm should be versatile and compatible with different platforms while focusing on agility and dynamic movement rather than precision, as maneuverability is more crucial for disintegrating the solid material in the tanks. Durability is also vital for operating in harsh conditions with minimal maintenance, and the arm should be robust enough to handle the radioactive environment. Additionally, the positioning of the arm and integration with existing systems, such as Spot's Core I/O, need to be carefully considered to maximize functionality and data transfer capabilities.

#### *1.1.5. Needs Analysis*

A successful 5 DoF robotic arm design must be dynamic and agile to effectively operate in complex environments, such as cleaning the interiors of plutonium tanks. The arm should semi-autonomously perform intricate movements, adapting to various spatial constraints while maintaining a high degree of precision. Adaptability is crucial for navigating around obstacles while avoiding collisions.

The arm's dynamic capabilities will allow it to execute sweeping and contour-following motions essential for thorough cleaning, particularly in areas with intricate geometries like ridges and curves. Rapid response to changes in the environment is vital; the arm must be easy for a human operator to manipulate and move through computer inputs.

The robotic arm must provide precise and accurate control to ensure thorough waste removal without damaging the tank walls. Also, the arm must exhibit versatility, allowing it to adapt to various cleaning protocols and conditions. The primary focus must be on the arm's agility, maneuverability, and adherence to the designated needs. As mentioned previously, our needs analysis follows our mission statement. There is a need for a technology that has 5 DoF and can move through its full range of motion in each degree of freedom around 1 Hz.

## 1.2. Design Requirements

The design of the 5 DOF robotic arm is guided by functional, structural, and performance requirements to ensure each joint operates effectively while maintaining durability and ease of assembly. Each joint (J1-J5) serves a distinct purpose within the system, requiring specific design considerations. The arm's weight must remain under 14 kg to ensure that it does not exceed load-bearing limits, allowing for ease of movement without overloading the motors.

Torque output is an important factor, with each joint needing to operate within a range of 2-10 Nm to provide sufficient force for controlled movement. J1, the shoulder joint, must support the full weight of the arm while allowing smooth rotational movement. To achieve this, a cross-roller bearing is used to distribute high torque loads, preventing premature wear on the motor shaft. J2 and J3 must generate enough torque to enable vertical and elbow-like motion while keeping weight constraints in mind.

Positional accuracy is essential for precise manipulation tasks, with a recommended accuracy between 10-30 mm. This ensures the robotic arm can interact with objects without excessive deviation from intended positions. J5, which controls wrist movement, requires particularly smooth motion to enhance dexterity and avoid sudden jerks. Additionally, the robotic arm must achieve a reach of at least 0.67 meters, similar to that of a human arm.

To maintain operational efficiency, the robotic arm must be capable of executing movements at a frequency of at least 1 Hz, ensuring responsiveness during tasks. High-frequency motion is important for applications requiring repeated or continuous movement.

To address these performance requirements, the team carefully selected materials and design features to balance durability, efficiency, and ease of manufacturing. The initial prototype utilizes PLA for its low cost and high printability, while the final version will use PETG for increased strength and heat resistance. Considerations like these collectively ensure that the robotic arm meets its performance requirements while maintaining a structurally sound and functional design.

## 1.3. Function Structure

The robotic arm converts electrical energy into mechanical motion through its five degrees of freedom. The major functional blocks include power input, control processing, actuation, and end-effector manipulation. The first subsystem, J1 (Shoulder Joint), converts rotational motion from the Brushless DC motor into high-torque movement. The cross-roller bearing supports the entire arm's weight, reducing friction and preventing stress on the motor shaft. The second subsystem, J2 (Vertical Translation Joint), provides up-and-down movement to adjust the arm height. This subsystem requires a parallel motor and bearing operation to ensure smooth, controlled motion without unwanted tilting. The third subsystem, J3 (Elbow Joint), functions similarly to J2 but introduces an additional bending motion, enhancing reach and articulation. This joint must balance strength and weight to avoid excessive loading on lower joints. The fourth subsystem, J4 (Forearm Rotation), allows rotational freedom similar to a human forearm, enabling fine adjustments to the orientation of the arm. The motor and bearing are optimized to be thinner and lighter weight. The fifth subsystem, J5 (Wrist Joint), provides wrist-like tilting movement, essential for precision tasks. This joint ensures the end-effector can orient itself properly for manipulation. By considering sub-systems such as 3D-printed housings, fastening systems, and electrical wiring systems, the robotic arm maintains balance, ensuring that all performance requirements are met.

# 2. System Description

The team's robotic arm consists of five main subassemblies. The team has divided the subassemblies based on the number of motors/joints. **Figure 1** below is the final assembly of the entire robotic arm including the base and aluminum extrusions it will be fastened to (**Appendix D**).

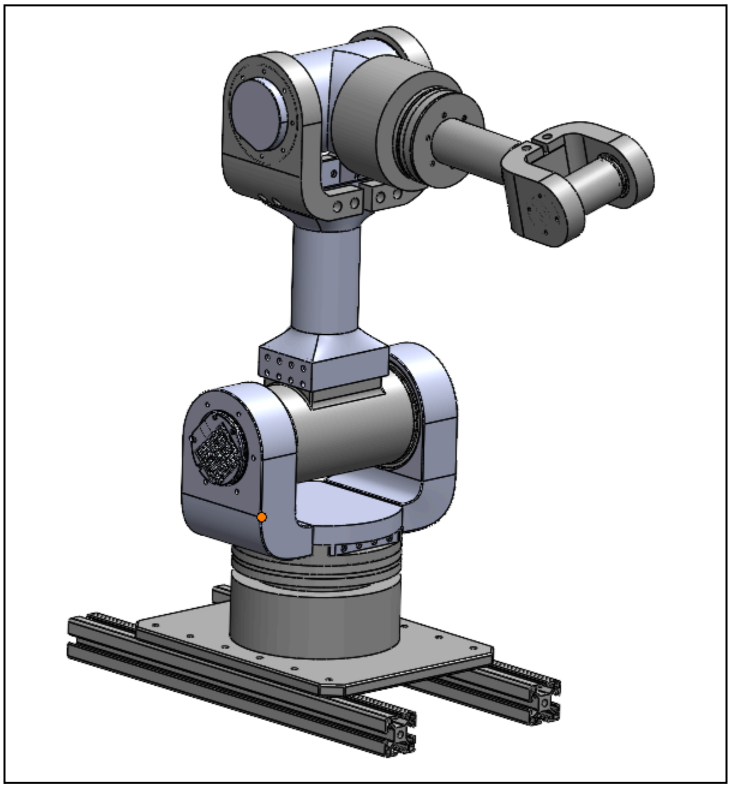


**Figure 1**: Final CAD Assembly

## 2.1. J1 Subassembly

**Figure 2** below is the J1 Subassembly. The assembly contains a variety of 3D-printed parts with the main purpose of holding the motor and bearing vertically on top of each other. J1 includes five main components: the J1 Motor Holder, J1 Mushroom Cap, J1 Motor Cover, J1 Motor, and J1 Cross Roller Bearing. The individual pictures of each component can be found in **Appendix D.** The J1 Mushroom Cap essentially connects to both the J1 Motor and J1 bearing to allow for movement. The reason we chose this method is because the J1 Joint (shoulder) carries the entire weight of the arm, meaning it experiences extremely high torque loads. A cross-roller bearing such as the one we chose reduces friction and distributes the load, preventing excessive wear and power loss. The Brushless DC motor for J1 provides the rotational force to overcome inertia and move the joint effectively. Without the bearing supporting the motor, the weight of the arm would directly stress the motor shaft, leading to premature failure. The J1 Mushroom Cap is unique in that it is also the part that interfaces J1 to J2 by including heat set inserts for assembly.

There are a variety of holes in this subassembly, ranging from M4-M6. The holes in our 3D printed parts are all clearance fit holes, which significantly simplifies assembly. Clearance holes ensure that bolts and screws slide through holes without resistance, making it easier to align with components without threading issues between parts. By preventing threads from engaging with both components, clearance holes allow for clamping force without excessive friction or stress on the fasteners.

A design challenge we struggled with was the tolerance of these clearance holes after printing. After talking to a team at the Rellis Bush Development Complex where they produce robots, they recommend having a minimum of 0.4 extra clearance from the original hole size. So for example a M4 hole would need a 4.4 clearance hole. This proved to be too small after 3D printing J1. So the team decided to increase the tolerance to 0.6 which has alleviated the stress on the fasteners, as well as made the design simpler. This justification for clearance holes follows the same for the rest of the subassemblies.

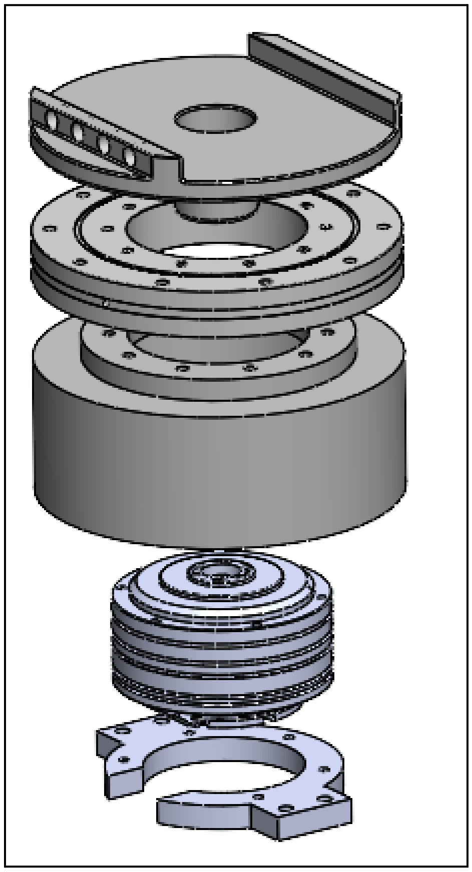


**Figure 2**: J1 Assembly

## 2.2. J2 Subassembly

The J2 assembly features a different design than the J1 assembly as it allows for an up-and-down translational movement. The J2 movement enables the robotic arm to reach different heights, allowing it to interact with objects at various levels without needing to reposition the entire base. J2 is essential for increasing the overall workspace of the arm. **Figure 3** below shows the motor and bearing on opposite sides of a cylinder that allows for their connection. J2 consists of five main components: the J2 Motor Holder, J2 motor, J2 Ball Bearing, J2 Bearing Holder, and the J2 Cylinder. The individual pictures for these components can be found in **Appendix D**.

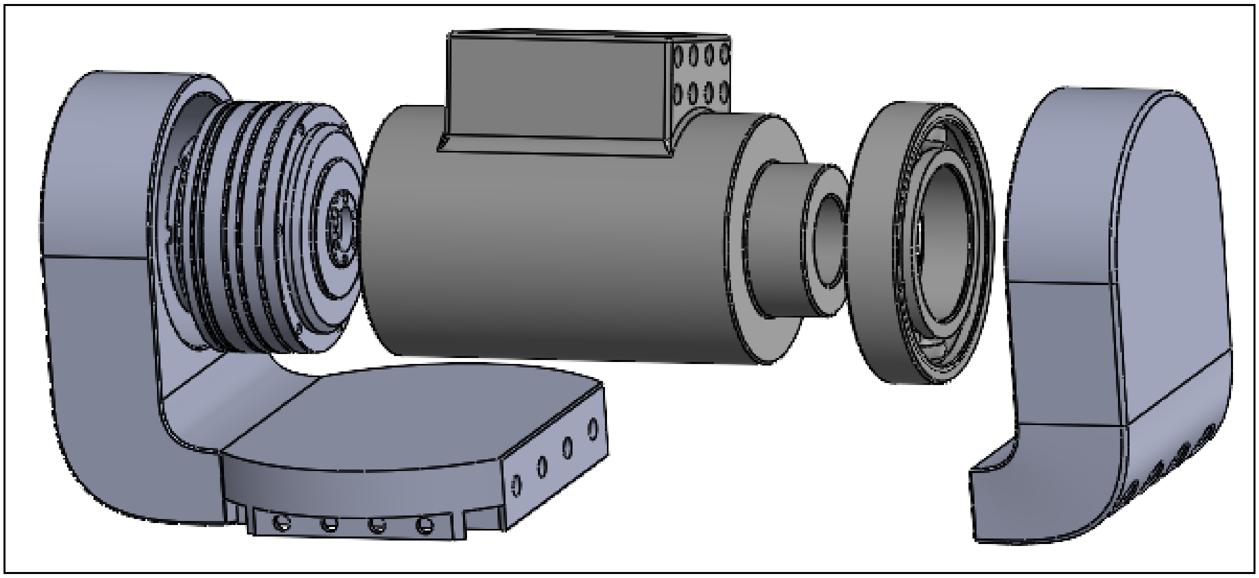


**Figure 3**: J2 Assembly

**Figure 4** shows the construction of every component up to the Bicep linkage. Due to missing soldering tips and fasteners, a mock assembly can be seen below of how these subassemblies work together.


**Figure 4**: Base, J1, and J2 Assembly without fasteners

## 2.3. J3 Subassembly

The J3 Assembly seen in **Figure 5** provides the same up-and-down movement that an elbow on a human provides. The J3 assembly consists of six main components: the bicep, J3 Motor Holder, J3 Motor, J3 Ball Bearing, J3 bearing holder, and the J3 cylinder. It features a similar concept to J2 for simplification purposes. The bearing and motor present in J3 are smaller due to weight constraints. The J3 motion similar to an elbow is crucial in robotic arms as it enhances dexterity, reach, and precise control. Without J3 motion, other joints would have to compensate with more complex movements, making control harder and reducing efficiency.

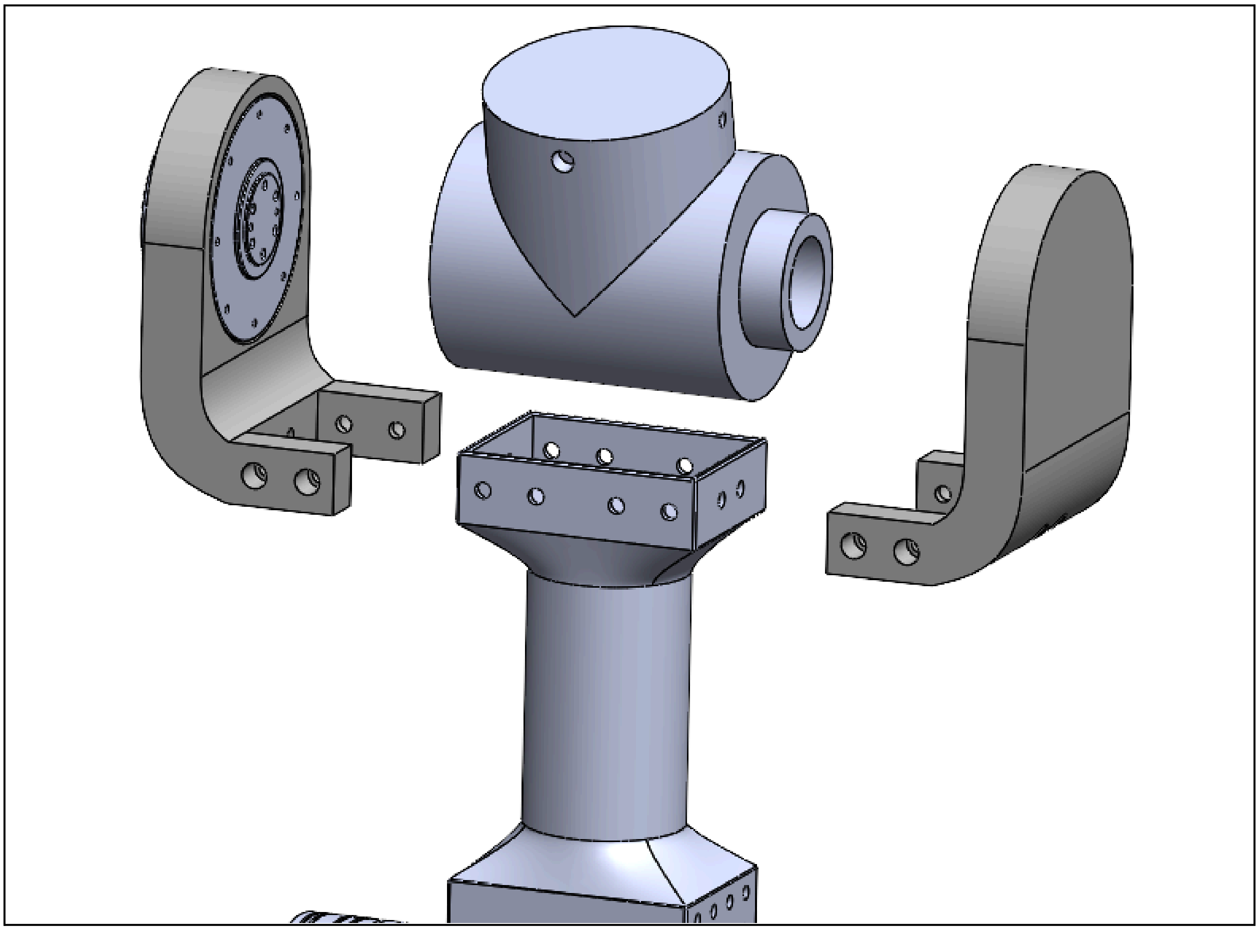


**Figure 5**: J3 Assembly

## 2.4. J4 Subassembly

The J4 assembly shown in **Figure 6** is crucial for allowing the rotational movement that a human elbow provides. The J4 assembly consists of five main components: the J4 Motor Holder, J4 Motor Cover, J4 Cross Roller Bearing, J4 Mushroom Cap, and the J4 Motor. The pictures of each component can be found in **Appendix D**. J4 acts the same as J1 except instead of interfacing with the base it interfaces with the J3 Cylinder. It also features the same motor as J3.

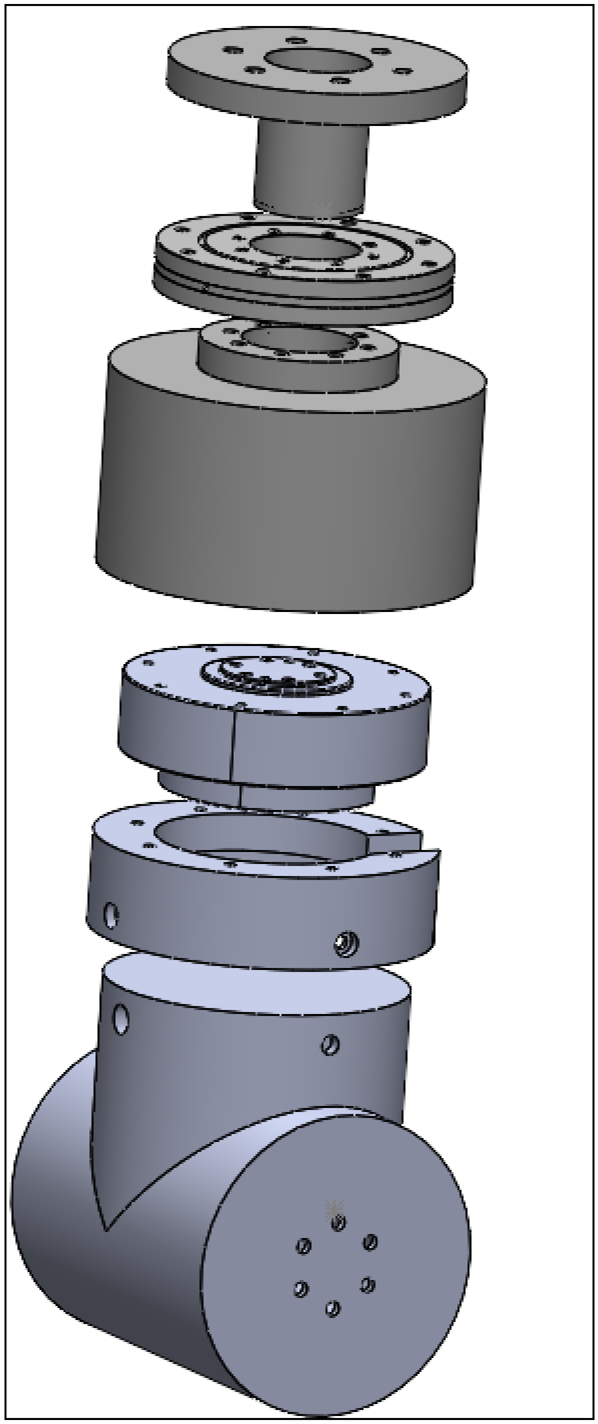


**Figure 6**: J4 Assembly

## 2.5. J5 Subassembly

The J5 assembly can be seen below in **Figure 7**. The J5 assembly includes seven main components: the Forearm, J5 Motor Holder, J5 Bearing Holder, J5 Cylinder, J5 Cylinder Cap, J5 Motor, and J5 Bearing. The J5 assembly provides the same up-and-down movement that a wrist on a human arm provides. The J5 joint is essential because it provides fine control, orientation flexibility, and dexterity during manipulation tasks. J5 allows the robotic arm to tilt the end-effector, ensuring it can properly grasp/interact with objects.

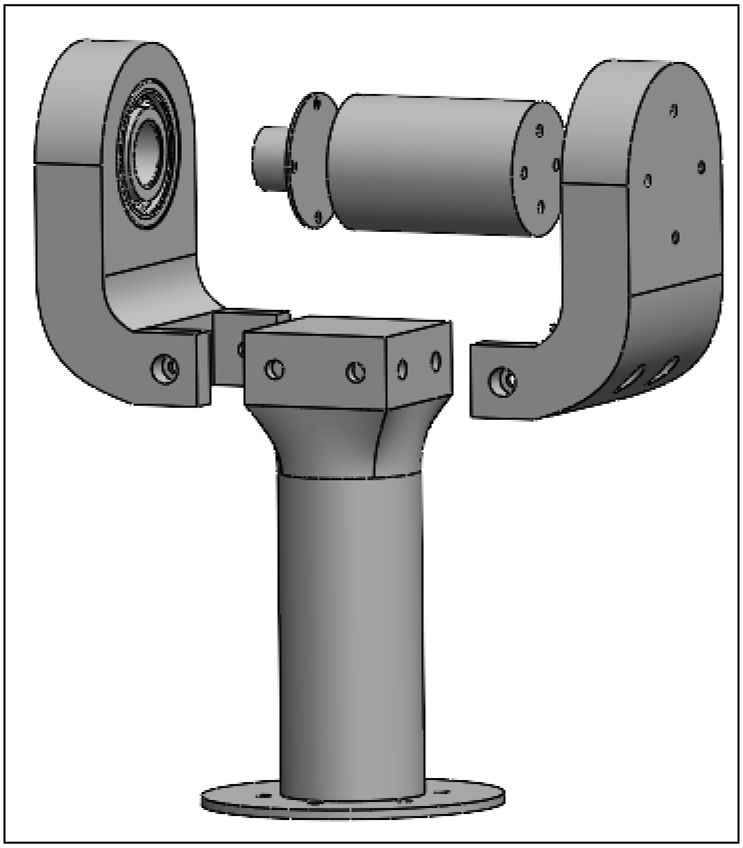


**Figure 7**: J5 Assembly

## 2.6. Material Selection

For the initial model of the robotic arm, PLA is the ideal material due to its ease of printing, low cost, and accuracy, making it perfect for testing out designs and making quick adjustments. PLA prints smoothly with minimal warping, so the team can focus on refining the shape and functionality without worrying about print failures. But for the final version, PETG is the better option since it's stronger, more flexible, and resistant to heat and impact, which means the arm will hold up better under real-world conditions. Unlike PLA, PETG won't become brittle over time or warp if it gets too warm. Using PLA for prototyping and PETG for the finished arm strikes the right balance between fast, cost-effective development and long-term durability. Due to the sheer amount of parts in our robotic arm, the team has included all pictures of the SolidWorks parts in **Appendix D** instead of individual engineering drawings for each.

## 2.7. Fastener Selection

The fastener selection process for the robotic arm began by considering several key constraints: motor sizing, cost, and the presence of vibrational forces. These limitations significantly influenced the choice of fasteners, guiding the selection toward a balance of performance, cost-effectiveness, and stability.

Motor sizing constraints dictated the available space for fasteners, particularly at the motor mounting interfaces. The specific design of the chosen motors threaded holes from Joints J1 through J5 limited the sizing for fasteners and required certain fastener types (e.g., M3, M4, M5, M6), as well as being easily accessed in the confined space. Socket head cap screws were selected because of their compact head design, which minimized the required clearance, allowing for secure attachment of the PLA components to the motor without interfering with other parts of the arm. To remain within budget, the team identified that most of these fasteners were bought in bulk, so the team decided to utilize the fasteners used for motor mounting within their specific joint for other attachments within that joint. This helped reduce cost; however, it is also important to note the process the team followed to ensure the structural integrity of the robot with the fastener selection. Another influence on the fastener selection of socket head screws was their application in high-torque environments.

A critical step in the design process was determining the maximum loads experienced at each joint. Although the team was not allocated the time or resources to properly calculate each respective value for each fastener, they were able to identify critical areas where loading and unloading may take place. The robotic arm's joints, particularly J1 and J2 (the shoulder and elbow joints), experience significant torque during operation due to its actuation properties as well as its distance away from the end effector. Socket head cap screws provide a connection capable of withstanding these high torque loads without loosening or stripping. This is also supported by the use of heat-set inserts in the PLA to prevent loosening under dynamic loads. Furthermore, the chosen socket head screws have a tensile strength of around 170,000 psi, which translates to a tensile weight of 880 kg to 1500 kg (dependent on the fastener size), which is well beyond our desired application, but may be appropriate for this application in the future. This high tensile strength is crucial for several reasons related to the robotic arm's operation. The fasteners need to be strong enough to withstand the weight of the payload, preventing the joints from being pulled apart, as well as the weight itself. The arm is designed to lift a payload of 2 kg at human arm length, and the high tensile strength of the fasteners ensures the robotic manipulator can handle this load both in static and mechanical operations. Socket Head Cap Screws are less likely to loosen or break under these conditions, ensuring the long-term reliability of the robotic arm. This combination of factors – their compact size, cost-effectiveness, suitability for high-torque applications, high tensile strength, and compatibility with our chosen motor mounting strategy (including the use of heat-set inserts) – made socket head cap screws ranging from M3 to M6 the optimal choice for this robotic arm design.

## 2.8. Electrical Selection

For the control design, the team chose to create a system utilizing an MCP 2515 CAN Bus and Arduino Uno. This setup was chosen because it has the potential to control multiple motors at the same time from one central source. To begin the control system implementation, a basic control flow diagram was created to demonstrate the flow of device communication. The connection of communication is depicted as seen in **Figure 8.**

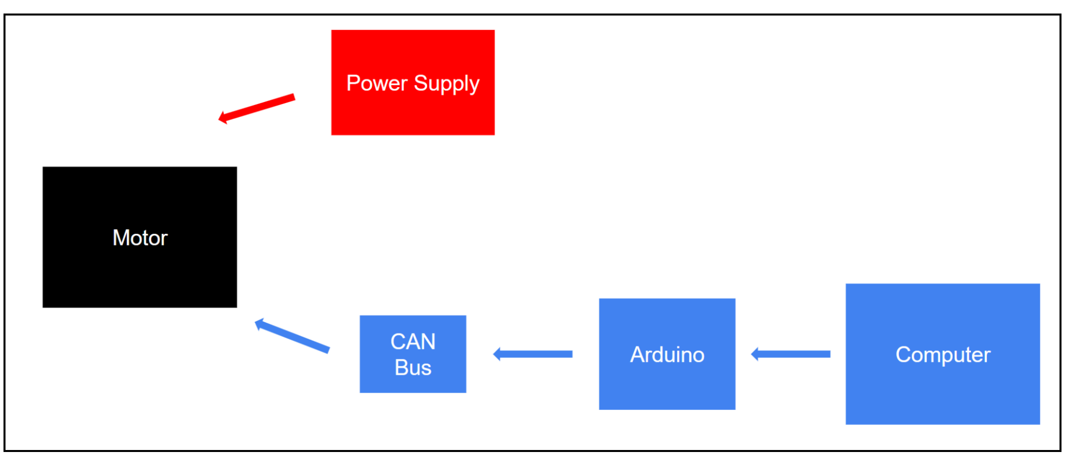
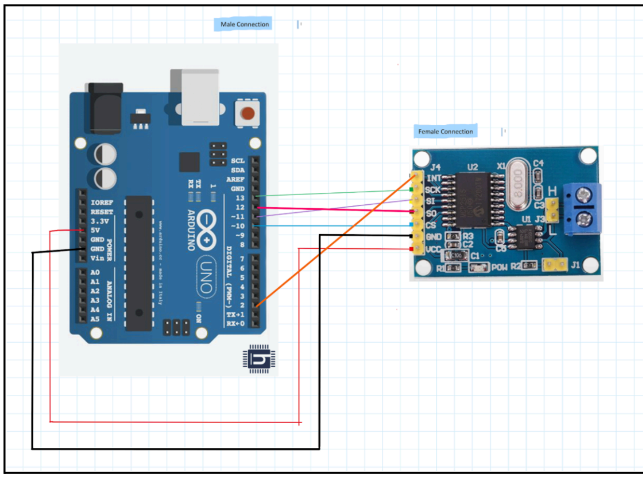


**Figure 8**: Communication Order for Controls System

After the connection was established, the next step for implementation was to create a wiring plan for the communication between the CAN Bus and Arduino Uno. The wiring diagram can be seen in **Figure 9.**




| MCP2515 | Arduino Uno | Cubemars AK10-9 |
|---|---|---|
| VCC | 5V | - |
| GND | GND | GND |
| CS | Pin 10 | - |
| SCK | Pin 13 | - |
| MOSI | Pin 11 | - |
| MISO | Pin 12 | - |
| INT | Pin 2 | - |
| CANH | - | CANH |
| CANL | - | CANL |

**Figure 9**: Wiring Diagram for CAN Bus and Arduino Uno Communication

The pin connections between the devices influence the software commands that are utilized to create movement in the motors. The Arduino is connected to a laptop through an A-B type cable connection, and the motor is connected to the CAN Bus through CAN High and Low wires that were provided by the manufacturer. The final setup with the motors and power supply can be seen in **Figure 10.**

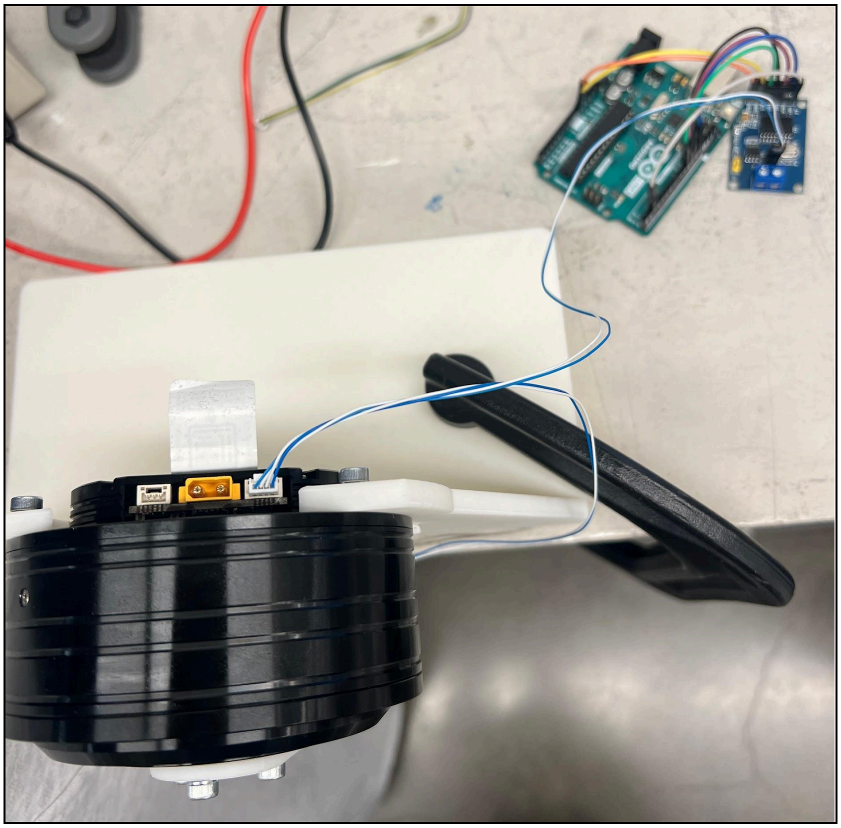


**Figure 10**: Controls System Complete Set Up

This system is controlled through the Arduino IDE using a variation of the C language. This system offers robust communication, multi-device networking, and real-time performance.

# 3. Analysis of Design

The analysis of design is a critical phase in ensuring a project's feasibility, efficiency, and success. This section will address key logistical challenges, including sourcing materials, manufacturing constraints, and timeline management. It will also evaluate the design using an embodiment design checklist to ensure functionality, reliability, and ease of assembly. Additionally, a risk analysis will be discussed to identify potential failures and mitigation strategies, while a budget and bill of materials (BOM) will outline total project spending.

## 3.1. Logistical Challenges Faced

MEEN 402 has focused on the manufacturing and testing of our design. With that being said, it is important to note that in the design process, the team couldn't 100% conceptualize the complexity of the device until it was in the fabrication process. This complexity has led to numerous logistical challenges that have been faced, influencing the redesign of different components of the team's design. These logistical challenges, so far, have been presented in the form of manufacturing and assembly challenges, motor control, budgeting, and outsourcing issues plus limited time and resources.

Several manufacturing and assembly challenges arose during the fabrication of the robotic arm. One issue involved the tolerances for threading fasteners through PLA parts into heat-set inserts. The original tolerance of +0.4 proved too tight due to printing uncertainties. During manufacturing, some holes were not threadable. This required the team to adjust the tolerance to +0.6, which resolved the threading issue but highlighted the importance of accounting for PLA printing variations in the design phase.

The team also discovered the critical role of infill percentage in the strength of 3D-printed parts. The initial base design, printed with a low infill percentage, was weak and brittle. This was particularly concerning as the base is responsible for supporting the entire robotic arm. The team redesigned the base with a higher infill percentage to ensure sufficient strength and stability. Furthermore, the team learned the importance of print orientation and part layout on the print bed. Curved and filleted sections of parts, especially those near the base of the printer, were susceptible to gravitational effects during the 3D printing process, affecting the part's dimensional accuracy, and thus requiring specific orientations to ensure proper dimensions.

Finally, despite attempting to avoid press-fit fasteners due to the uncertainties of PLA printing, the team encountered clearance issues with some fasteners. Specifically, the heads of fasteners connecting the J1 motor holder to the motor cap in the case where the fasteners protruded from the back of the motor holder. This protrusion interfered with the motor holder's ability to sit flush on the 3D-printed base. Consequently, the base had to be redesigned to accommodate these fastener head obstructions, and can be seen in **Figure 11**.

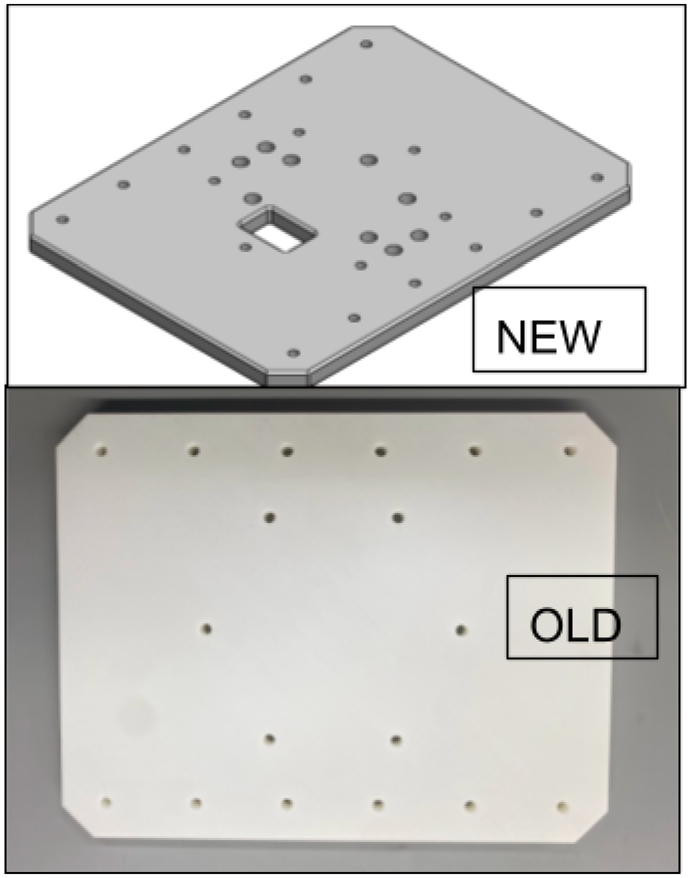



**Figure 11:** Base Redesign to ensure Flush Mounting

On the control side, the team has continuously been troubleshooting issues with the Arduino to CAN Bus connection to the motors for actuation and control. The team originally implemented an Arduino to CAN Bus connection (see **Figure 9**). These connections, like many interface connections between Arduino and CAN Bus, are fairly standard. However, hard-coding the Arduino to control the motor has presented challenges. Due to the team's limited knowledge of C language, this has led to delays in motor control, further compounded by the influence of other facets of the project and limited resources (personnel). To address this, the team was able to test both the J1 and J2 motors (motor names) using an R-link to an Upper computer connection provided by Cube Mars. This was successful and allowed for individual motor testing, consistent with the testing plan outlined in 401. The team hopes to continue troubleshooting the Arduino to CAN connection in pursuit of our stretch goal of comprehensive motor control.

On the project management side of things, the team faced logistical challenges in budgeting due to the current state of the US government's economic relations with foreign countries. When purchasing our motors (motors listed and cost), the team encountered a $500 tariff fee that was immediately deducted from the team's budget and was not planned for. This significantly impacted the importance of cost reduction and influenced the team to cancel any further orders from outside the US. Fortunately, through collaboration with our sponsor at LANL, the team was able to receive the necessary foreign components from the LANL research laboratory.

Through these logistical challenges, the team has learned to recognize and streamline these issues by developing new design techniques to iterate on older designs. The team has also adopted a forward-thinking and proactive communication method with all partners in the 402 capstone project (professors, researchers, and sponsors).

## 3.2. Embodiment Design Checklist

As the team transitioned from MEEN 401 to MEEN 402 with the concept of embodiment design, the focus shifted from qualitative to quantitative analysis, uncertainty to certainty, and concept to product understanding. Several critical factors contributed to the embodiment design including our concepts' functionality, efficiency, and manufacturability. Throughout this process, the key features below were defined, understood, and reflected on for our project.

- Function: The design must satisfy customer needs, fulfill its intended purpose, and incorporate necessary auxiliary functions
- Working Principles & Form Solutions: Selected components and architecture must provide the desired performance while minimizing disturbances and unwanted byproducts
- Layout, Geometry & Materials: The design should balance durability, material efficiency, structural integrity, and environmental resistance
- Energy & Kinematics: Efficient energy transfer and controlled motion must be maintained for optimal system behavior
- Safety & Ergonomics: User safety, product reliability, and human interaction considerations must be addressed
- Production & Quality Control: Manufacturing processes should be feasible and cost-effective while maintaining appropriate tolerances and quality standards
- Assembly & Transport: The design should simplify assembly procedures, reduce part count, and ensure safe transport and packaging
- Operation & Life Cycle: Factors like noise, vibration, recyclability, and sustainability must be considered for long-term usability
- Maintenance, Costs, & Schedules: The product should allow for easy maintenance and adhere to budget constraints under certain time limits

After careful consideration of the features mentioned above, the team came together and assessed the project by its percentage of completion and the status of the design per feature. The team also assessed any unresolved issues within each feature and assigned a corresponding recovery plan along with the person responsible for its completion. Lastly, the team predicted the expected resolution date to stay on track with each milestone. A complete assessment of these key features can be found in **Appendix E.**

## 3.3. Risk Analysis (FMECA and FTA)

Analysing risks is the most important component in design. Risk is the possibility of something bad happening while risk management is the process of managing risk with cost, schedule, and other programmatic considerations. The two components of risk include: What is the probability that it will occur and if it occurred, how severe would the outcome be? A model that is commonly used to identify risks is the Failure Modes, Effects, and Criticality Analysis (FMECA). This allows a design team to examine the different ways in which a system failure can occur, starting from the components, the potential effects of failure on system performance and safety, and lastly, the seriousness of effects. The team was able to complete this analysis for their robotic arm by identifying each failure mode and evaluating the effects of its failure. A full FMECA analysis is included in **Appendix F** with the highest-rated failure mode for Fatigue from Repeated Motion on Crucial PLA supports receiving a RPN score of 144**.**

To evaluate reliability and avoid failure, a Fault Tree Analysis (FTA) can be used. This analysis is a deductive reasoning technique that focuses on one particular high-level failure event and displays the various combinations of faults and failures that can result in the high-level fault/failure. The strength of FTA as a qualitative tool is its ability to break down a failure into basic smaller failures and human errors. It can also become quantitative by including each failure's probabilities. The team also completed an FTA analysis on the highest-rated failure mode being the Fatigue from Repeated Motion on Crucial PLA supports which can be seen in **Figure 12.** When creating an FTA for this failure mode, 4 crucial causes for the overall failure were identified and 3 causes for each crucial failure mode were identified. The use of both AND and OR gates was used to represent the various ways the system could fail. The FTA allowed the team to identify crucial causes of failure to then identify mitigation techniques or plans to avoid failure.

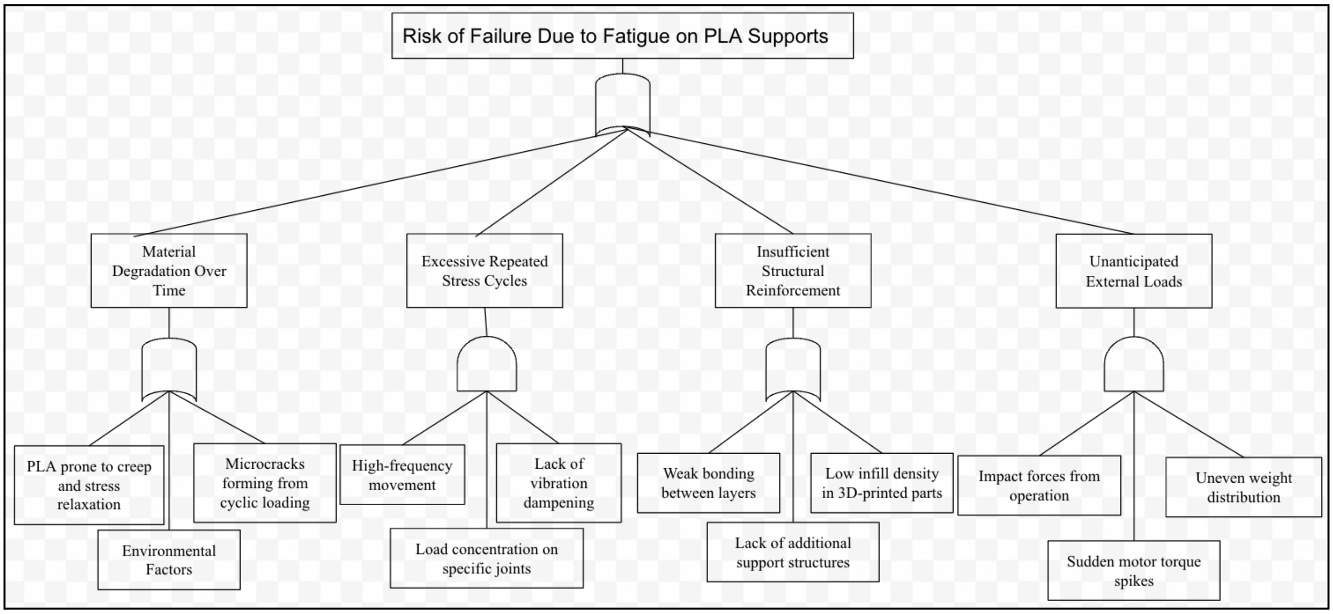



**Figure 12:** FTA Analysis for “Risk of Failure Due to Fatigue on PLA Supports”

## 3.4. Design Validation

The primary validation technique for our design is physical prototyping, assembly, and individual joint testing. This approach is essential for identifying physical limitations, interfaces, structural integrity, and the performance of the team's actuators. It's important to note that aligning prototyping with design requirements ensures the robotic arm meets customer needs and provides quantitative performance metrics (e.g measuring rotational speed in rad/s to confirm the 1 Hz operational frequency, quantifying torque output in Nm to ensure the arm can handle its weight and the potential required payload, and conducting a physical inspection of fastener integrity to ensure no loosening or deformation occurs). To date, assembly of the base has been completed, however, due to supply chain disruptions impacting the timeline, the joint components (J1 - J2) have only been printed using 3D-printed PLA but have not yet been assembled. Material and fastener selection for all joints (Base - J5) have been completed, and the initial electrical setup with an R-Link to Upper Computer connection has been successful. As for the testing portion of our validation, the team will validate the position, speed, and torque of each joint actuator using the R-Link and Upper Computer connection.

Preliminary results show successful communication between the Upper Computer control software and the J1 and J2 motors, which are the same model. Assembly tolerance issues were iterated upon and were addressed with a final 0.6 mm clearance adjustment in 3D-printed parts. Ongoing troubleshooting focuses on the communication issues within the Arduino and CAN bus electrical subsystem for motor actuation. As testing progresses, data will be compiled to verify each joint meets the required frequency of operation and other performance benchmarks, outlined in the customer needs and embodiment design.

## 3.5. MEEN 401/402 Budget

The Bill of Materials for MEEN 401/402 has been an evolving document, adapting to design changes, safety additions, and the inclusion of sponsor-funded components. Each capstone team within the Mechanical Engineering department was allotted a $5,000 budget for their project. As of today, approximately $3,500 has been spent, with the majority allocated to motors and the corresponding bearings for each joint.

At the beginning of the semester, additional customs fees were applied to the motor order, requiring the team to spend an extra $500. Concerned about exceeding their budget, the team reached out to their sponsor, explaining the financial constraints and the need for additional funding. In response, the sponsor provided the two most expensive components—the remaining motors and a power supply—allowing the team to allocate their remaining budget toward other necessary components. With this support, the team was able to purchase a safety cage and all the remaining parts required to complete the project.

Additionally, the team has taken advantage of resources available at the FEDC and within the Mechanical Engineering department, borrowing equipment and parts that would have otherwise needed to be purchased. For example, the team has been able to use the 3D printers in the Rapid Design Studio (RDS) to fabricate PLA components at minimal cost.

While not all parts have been purchased yet, the team still plans to acquire the remaining electrical components. If the budget permits, they also intend to reprint the PLA parts using a more durable filament to enhance the robot's structural integrity and long-term durability. **Figure 13** provides a summary of the current Bill of Materials. The final product is estimated to cost under $4,000.

| A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|
| **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 | $40.47 | | |
| 5 | 1 | Bearing - Crossed Roller | J1 Bearing: 80mm shaft High-Load Face-Mount Crossed-Roller Bearing | McMaster-Carr | vw.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 | vw.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 | $217.66 | | |
| 9 | 1 | Ball Bearing | J5 Bearing: 20mm shaft Ball Bearing | McMaster-Carr | vw.mcmaster.com/ | $13.12 | $13.12 | | |
| 10 | 1 | 94180A371 | M6 x 1 mm Thread Size, 7.6 mm Installed Length | McMaster-Carr | w.mcmaster.com/9 | $13.80 | $13.80 | | |
| 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 | 1 | 94180A361 | M5 x 0.8 mm Thread Size, 6.7 mm Installed Length | McMaster-Carr | w.mcmaster.com/9 | $17.86 | $17.86 | | |
| 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 | 9.99 | | |
| 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 | | |
| | | | | | Additional Customs Fee | | 514.41 | | |
| | | | | | Shipping (McMaster) | | 29.13 | | |
| | | | | | | **TOTAL** | $3,469.15 | | |

**Figure 13:** Current Budget/Bill of Material

# 4. Balance of Semester Plan

## 4.1. Expected Deliverables

The team has outlined the final deliverables expected for the engineering project showcase in the MEEN 402 senior design project success agreement. This document was implemented during week 3 of the 2nd semester of Capstone which froze design requirements and required future design requests to be considered through change order requests. These deliverables will be given to the sponsor after the project. The complete list of final deliverables is detailed below:

- Fully assembled 5 DOF robotic arm prototype
- SolidWorks CAD model of fully assembled 5 DOF robotic arm
- Base and J1-J5 individual SolidWorks CAD assemblies and engineering drawings
- Circuit block diagram of 5 DOF motor electrical design
- Assembly Instruction Manual
- Final Report outlining work performed in MEEN 402
- Final Presentation outlining work performed in MEEN 402

### *4.1.1. Fully Assembled 5 DOF Robotic Arm Prototype*

Fully assembled 5-degree-of-freedom robotic arm prototype designed for speed. Constructed of 3D printed linkages and CubeMars brushless DC motors on an aluminum extrusion base. Each joint has brushless DC motors, allowing for movement across five axes. The robot will be controlled through a connection to a computer and powered by an 80 V bench power supply. The most recent CAD design of the final design can be seen in **Figure 14.**

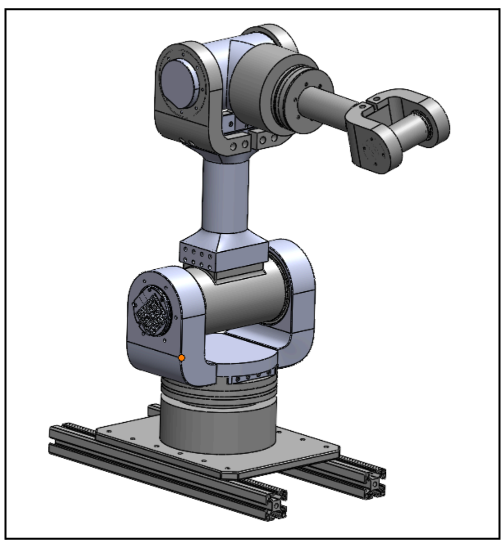


**Figure 14**: Final CAD Design

### 4.1.2. SolidWorks CAD Model of Fully Assembled 5 DOF Robotic Arm

SolidWorks CAD model represents a fully assembled 5-degree-of-freedom robotic arm designed with realistic motion constraints and precise tolerancing for assembly. The model includes a detailed mechanical structure that showcases individual components: linkages, joint housing, motors, and base.

This model provides a comprehensive foundation for further development, simulation, and real-world fabrication.

#### *4.1.3. Base and J1-J5 Individual SolidWorks CAD Assemblies and Engineering Drawings*

This set of SolidWorks CAD assemblies and engineering drawings provides a detailed breakdown of the base and individual joints for the 5-DOF robotic arm. Each assembly is designed to ensure structural integrity, motion control, and seamless integration within the full robotic arm system. Each joint and base assembly is accompanied by detailed 2D engineering drawings. This ensures smooth fabrication, assembly, and testing of the 5-DOF robotic arm.

#### *4.1.4. Circuit Block Diagram of 5 DOF Motor Electrical Design*

The circuit block diagram illustrates the electrical architecture responsible for powering, controlling, and coordinating the arm's movement. The design ensures reliable communication between the microcontroller, motor drivers, and power supply, enabling precise control of each joint. The circuit block diagram visually maps out the power flow, signal paths, and control interfaces, providing a clear electrical design layout for implementation and troubleshooting. It serves as a fundamental reference for wiring and firmware development in the robotic arm system.

#### *4.1.5. Assembly Instruction Manual*

The assembly instruction manual provides a step-by-step guide for constructing the 5-DOF robotic arm to ensure accurate assembly and optimal performance. This manual provides an overview of the assembly of the robotic arm as well as step-by-step instructions for each joint. The manual contains an introduction, safety precautions, assembly steps, testing and troubleshooting, maintenance and care, and support and contact information.

#### *4.1.6. Final Report Outlining Work Performed in MEEN 402*

This report discusses the final system design, operation, and validation. The target audience for this report is an individual who knows nothing about the project. Its contents will include a cover page, table of contents, glossary table, introduction and problem definition, system description, analysis for design, broader impacts of design, summary, acknowledgments, references/citations, and an appendix. This report will be a narrative to explain the project and the steps taken to complete it.

#### *4.1.7. Final Presentation Outlining Work Performed in MEEN 402*

The final presentation for MEEN 402 provides a comprehensive overview of the work performed throughout the project, highlighting the design, development, and implementation of the 5-DOF robotic arm. This presentation serves as a formal conclusion to the project, showcasing key achievements, challenges, and recommendations for future continuation of the project. The outline of the presentation will include an introduction and project objectives, design and development process, mechanical and electrical system integration, testing and performance evaluation, final deliverables, and a conclusion and Q&A.

## 4.2. Remainder of Embodiment Design

This section details the team's progress on the embodiment design checklist, and what is left to be considered. The team has a plan to validate the design fulfills the core customer needs of maneuverability, speed, and sizing, essential for cleaning nuclear waste tanks. The 5-DoF arm, with its human-like functionality, directly addresses the need for dexterous manipulation within the confined spaces of the tanks, a key challenge highlighted by LANL professionals. The team selected working principles, based on a sequence of revolute and prismatic joints, which are being evaluated for possible noise considerations, including motor vibration and gear backlash, with mitigation measures such as vibration dampening considerations for Kp and Kd values within the upper computer. The design focuses on a lightweight and compact (less than 14kg) design to accommodate the quadruped robot. Component forms are optimized for structural integrity and minimal material usage. Material choice (PLA for prototype, PETG for production) balances strength and producibility, responding to durability issues under operation. Factors like friction, wear, and corrosion resistance are being addressed through material selection and potentially surface treatments. Energy transfer efficiency and kinematic performance have been considered and optimized through careful motor selection. The team is evaluating the dynamic behavior of the arm to ensure smooth and controlled movements, minimizing vibrations and maximizing responsiveness, aiming for a movement frequency of at least 1 Hz. Preliminary safety analyses have identified potential hazards, such as electrical hazards and material failures, and the team is implementing safeguards like emergency stops and protective enclosures. Additional risk assessments (FMECA and FTA) have been outlined and considered. Although the arm is remotely controlled, ergonomic issues for maintenance and installation are being taken into consideration. The design is modular for ease of assembly and maintenance, and the team is creating an instruction manual for ease of construction and deconstruction. Transport, operation and control, and maintenance needs are being incorporated into the design as well as the assembly manual. Finally, the team is actively tracking costs and adhering to project schedules. The team is continuously evaluating and refining the design based on the findings throughout the embodiment design process to ensure a robust and successful outcome, meeting the project deliverables and customer needs.

## 4.3. Timeline for Validation

The project timeline for validation outlines the key phases involved in ensuring the 5-DOF robotic arm meets performance and functional requirements. This structured timeline covers the sequential steps from construction to final validation, including assembly, testing, simulation, analysis, and motor programming. The progress of the team is continually being monitored through the Google sheet displayed in **Figure 15**.

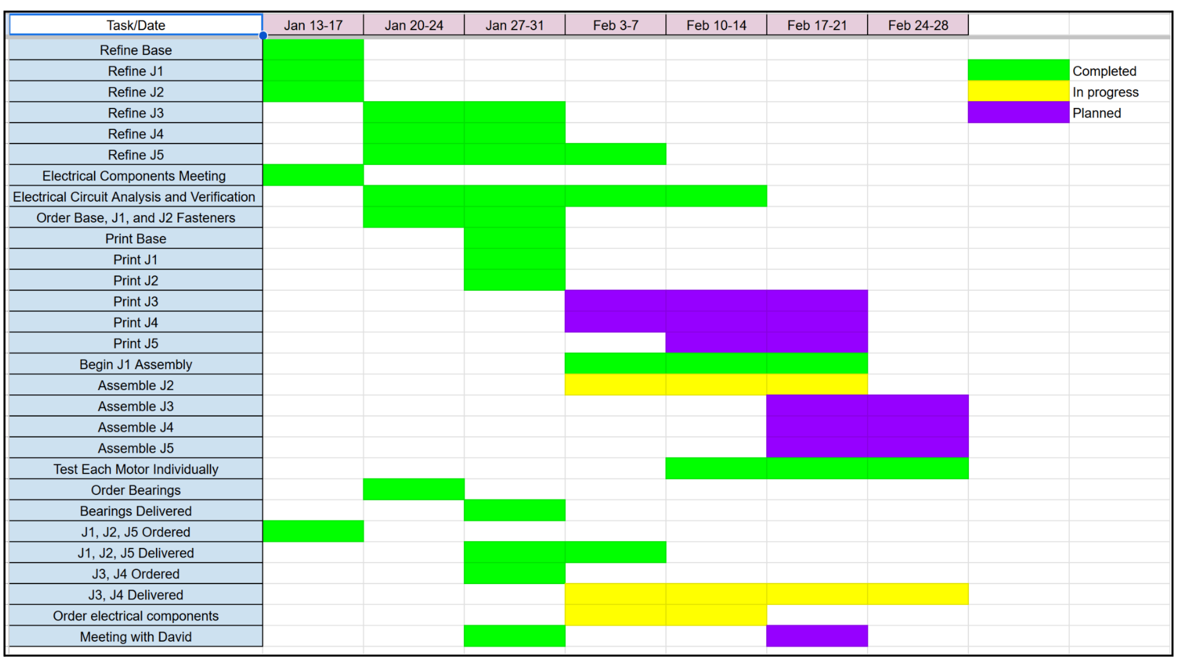



**Figure 15**: Capstone progress Google sheet

*4.3.1. Construction and Fabrication*

This phase includes 3D printing each linkage out of PLA plastic, sourcing motors, and obtaining a proper power supply. This phase occurs during the first 3 weeks of the semester.

*4.3.2. Assembly and Integration*

This phase consists of the mechanical assembly of the base and J1-J5 joints. This will be achieved through the implementation of the heat set inserts, the installation of motors, and bearings. This will also involve the wiring and integration of power supply, motor drivers, and control systems. This occurs during weeks four through six.

*4.3.3. Motor Programming and Control System Development*

This phase involves programming the motor controllers to communicate with the motors to create the desired fast movement. This will involve creating controller circuits and wiring diagrams. Each motor will be individually tested when connected to the motor mount to ensure predicted programmed movement. All electrical connections including wires, terminals, and connectors will be checked that they are properly secured and insulated. The kill switch will be activated to confirm immediate power cutoff in case of emergency before each run. This phase occurs during weeks seven through eleven.

*4.3.4. Testing and Calibration*

This phase includes initial movement testing to validate motor response and joint alignment. The motors are tested at each joint before assembly to ensure they are working properly and calibrated correctly. There are also error debugging and safety checks for electrical and mechanical components. This phase occurs during weeks twelve through thirteen.

*4.3.5. Validation and Final Adjustments*

This is the final phase of the validation timeline and it includes comprehensive system testing. The goal of this phase is to ensure that all of the requirements outlined in the project success agreement are met. This testing will validate that the joints can each move at 1 Hz independently without obstructing movement. The weight of the fully assembled robotic arm will also be validated to not exceed 14 kg and the reach of the arm should extend to a minimum of 0.67 meters. The maximum torque output will be within a range of 2-10 Nm and there will be a positional accuracy within 10-30 mm. This phase takes place in the final two weeks before the final presentation.

## 4.4. Future Concerns and Mitigation Plan

As the 5-DoF robotic arm is developed and validated, several future concerns may arise related to mechanical durability, control system stability, and human safety. Below is a list of future concerns for the team:

- Mechanical wear and structural integrity
- Software bugs and control system stability
- Safety and human interaction risks

*4.4.1. Mechanical Wear and Structural Integrity*

The team is concerned with the mechanical wear and structural integrity of the robotic arm as it is used in operation. Continuous motion can cause wear on bearings, joints, and fasteners leading to reduced speed and strength. Over time, stress concentrations may develop in high-load areas, increasing the risk of fatigue failure. To mitigate these risks, the team is incorporating high-strength material (PLA for prototype and PETG for production). The team is also increasing the infill of parts that experience a lot of strain and stress. This will protect the structural integrity of the robotic arm.

#### *4.4.2. Software Bugs and Control System Stability*

Another major concern is communication failures in the control system which can lead to unpredictable robotic motion and loss of precision in the robotic arm. This will be mitigated through testing that the control system works with each motor before system assembly.

#### 4.4.3. Safety and Human Interaction Risks

Uncontrolled motion, accidental collisions, and system malfunctions can create risks for nearby operators and equipment. To mitigate these risks the team is implementing an emergency stop mechanism into the design. A safety cage around the robot will also be implemented. This cage will restrict unauthorized access, prevent accidental interactions, and ensure that the robotic arm operates within a defined workspace.

# 5. Conclusions

The challenges present at The Hanford Site demand a solution that can overcome the complexities of removing solidified radioactive waste from underground tanks. The additional challenge that parallels this issue is having an environment of a confined and highly radioactive space. This capstone project, in collaboration with Los Alamos National Laboratory (LANL) and the team from Texas A&M, aims to provide a solution by designing a 5-Degree-of-Freedom human-like robotic arm attachment for a Quadruped Spot Robot. By developing this solution, the team's goal is to reduce environmental and safety risks associated with hazardous waste cleanup. In the intent to resemble human-like mobility and operational speed, the robotic arm will be able to access and manage waste in hard-to-reach areas in the tanks, which would be out of reach using traditional methods.

Building upon the foundational work conducted in MEEN 401, the team refined the robotic arm's design and implementation plan in MEEN 402. The finalized scope was established through the MEEN 402 Senior Design Project Success Agreement, freezing design requirements and defining change order protocols. The embodiment design process focused on fulfilling the core customer needs of maneuverability, speed, and sizing, ensuring the robotic arm could function effectively in confined spaces. Multiple risk assessments have been made to mitigate problems that the design could undergo along with plans on how these risks could be mitigated. Through careful planning, iterative refinement, and rigorous validation, this team plans to successfully develop a 5-DoF robotic arm that aligns with LANL's objectives. The team remains committed to refining the design, ensuring long-term reliability, and contributing to the broader goal of improving nuclear waste cleanup operations. By the conclusion of MEEN 402, the robotic arm plans to be fully assembled, tested, and ready for demonstration at the engineering project showcase in April 2025, marking a significant step toward practical deployment in hazardous environments.

# 6. References/Citations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[2] National Research Council. *The Hanford Tanks: The Status of the Technical Issues*. Washington, D.C.: National Academies Press, 2012, Hanford Site Test Bed Initiative Demonstration (TBI) | NRC.gov

[3] U.S. Environmental Protection Agency. "Hanford Site: An Overview." *EPA*, 2020, Hanford Site Spotlight | US EPA

[4] Poston, B. M., et al. "Current and Future Issues of the Hanford Waste Tanks." *Environmental Science & Technology*, vol. 45, no. 8, 2011, pp. 3461-3468,

[5] Dyer, R. L. "Robotic Systems for Hazardous Waste Cleanup: A Review." *Robotics and Autonomous Systems*, vol. 90, 2017, pp. 62-72.

[6] U.S. Department of Energy. *Environmental Impact Statement for the Disposal of Hanford Defense High-Level Waste*. Washington, D.C.: U.S. DOE, 1996,EIS-0113: Disposal of Hanford Defense High-Level, Transuranic and Tank Waste, Hanford Site, Richland, Washington | Department of Energy

# 7. Appendices

*Appendix A: Complete Technical Questions*

**Table A-1**: Justification for the Problem Statement and Mission Statement

| Technical Question | Explanation and Justification |
|---|---|
| 1. What is the problem really about? | The problem involves managing and removing hazardous radioactive waste from aging storage tanks at the Hanford Site. The waste has solidified, creating significant environmental and safety risks. The challenge is to design an advanced robotic solution for hazardous waste removal that can efficiently perform this task in a highly radioactive and confined environment. |
| 2. What implicit expectations and desires are involved? | Implicit expectations include the need for a solution that addresses immediate waste management issues while adhering to safety and environmental standards. There is a need for a robotic arm that can operate effectively in harsh conditions and adapt to various ergonomic situations. |
| 3. Are the stated customer needs, functional requirements, and constraints truly appropriate? | Yes, the design must ensure effective waste removal, minimize environmental impact, and operate safely within the tank's constraints. Constraints such as limited space, high radioactivity, and the need for remote operation are crucial considerations and align with the mission's goals. All of these constraints are appropriate. |
| 4. What avenues are open for creative design? Limitations on scope? | Creative design avenues include exploring innovation on joint movements, translation and rotational devices, control systems, and new waste handling techniques are all potential areas for innovation. Limitations include the project's 8-month timeframe, 7 DoF design, and the physical constraints of operating within the tank's confined space. |
| 5. What characteristics/properties must the product have (and not have)? | The robotic arm must be easily operable, precise, and capable of handling nuclear waste The arm should not be overly complex to operate and or fragile. |
| 6. What aspects of the design task can and should be quantified now? | Aspects that can be quantified now, due to the research, include the required torque levels for each joint, an estimation of the maximum force the arm can handle without tipping, the operational workspace, and the speed of action. These parameters are crucial for defining the arm's performance and ensuring it meets the operational requirements for waste removal. |
| 7. Do any biases exist with the chosen task statement or terminology? Has the design task been posed at the appropriate level of abstraction? | The task statement is generally unbiased and appropriately abstract, focusing on the need for an efficient waste management solution without specifying technologies. The only abstract problem the team ran into was the focus on the cleaning tool attachments priority in comparison to the robotic arm, however through Communication with Dr. Mascarenes this was clarified and resolved. |
| 8. What are the technical and technological conflicts inherent in the design task? | Technical conflicts include balancing the arm's strength and flexibility with size constraints as well as constraints imposed by the quadruped. As well as, the amount of torque that can be applied so that it doesn't infringe on the operation of the spot robot. Technological conflicts involve developing a control system capable of handling the arm's complexity while ensuring that it is easy to operate. Addressing these conflicts requires careful design choices and collaboration with Los Alamos National Laboratory and our Sponsor. |

*Appendix B: Customer Needs Interview Form*

**Table B-1**: The Customer Needs Interview form organized questions and customer responses from each interview. The form helped extract the team's needs and their associated weights for analysis.

| Question | Customer Statement (Rodrigo Ramon) | Customer Statement (Michael Tomlin) | Interpreted Need | Weight | Activity |
|---|---|---|---|---|---|
| What challenges or problems do you face in your current process for cleaning the wall of the tanks that you think a quadruped robotic arm could help solve? | The main challenges involve identifying the exact locations of plutonium buildup and distinguishing it from other materials, such as rust, on the wall. | Dry removal hasn't been attempted yet. The current robotic excavator is used to collect large amounts of material. The quadruped robot's goal is to handle the fine-detail cleaning that the excavator misses. | The robotic arm must be capable of precise, fine-detail cleaning to address residual contamination that large-scale excavation equipment cannot remove. It should include a sensing system to accurately identify and differentiate between various materials on the tank walls without causing damage | 3 | Performing detailed cleaning of tank walls to remove residual contamination |
| What features or functionalities would you consider essential for a quadruped robot arm in your operations (Hanford)? | The robot's dynamics must allow for stable operation, with a resting position or kickstand to support the arm near the wall, ensuring safety to prevent any damage | Stability is a primary concern, as the robot must not fall over in the tanks. The robot should lay down to provide a secure base for the arm's operations. | The quadruped robot arm must be stable and designed to operate safely in challenging environments. The system should also prioritize safety to prevent any damage to the tank walls. | 4 | Stabilizing the quadruped robot for secure operation during wall-cleaning tasks. |
| Given that the robot will need to operate in plutonium tanks and apply force to a wall, what particular environmental challenges or constraints (e.g., radiation, space limitations, surface conditions) should we consider in its design? | The design must account for environmental contact, including force sensing and position awareness, to manage the forces experienced by the end effector and minimize interaction with the environment. | The primary concerns are dust and debris, which could affect the robot's joints and components. While radioactivity isn't a major concern, protecting encoders and microprocessors is important. | The robotic arm must be designed to withstand harsh environmental conditions, with features for dust and debris protection, as well as force sensing and position awareness to minimize unnecessary interaction with the environment. | 4 | Protecting the robot's components and ensuring precise operation within harsh environmental conditions in plutonium tanks. |

| | | | | | |
|---|---|---|---|---|---|
| What specific motions would you expect the robot /robotic arm to handle regularly? (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. |
| What are your priorities in terms of performance (e.g., speed, precision, durability)? | Precision and durability are the top priorities, with speed being less important; the focus should be on performing tasks accurately. | Like Rodrigo, precision and durability are essential, with a strong emphasis on avoiding damage to the tank and ensuring accuracy in operations. | The robotic arm must prioritize precision and durability in its design and operation, focusing on executing tasks accurately while preventing any potential damage to the tank. | 5 | Ensuring precise and durable performance during operations to maintain the integrity of the tank while achieving accurate cleaning results. |
| What would success look like for you in terms of this robot's arm capabilities? ( What we need first) | Success for the robotic arm would be measured by its consistency in performance. | Success means completely removing identified waste from the wall and ensuring that the cleaning protocol effectively eliminates all contamination. A robust and consistent program is essential. | The robotic arm must demonstrate consistent performance and effectively remove identified waste from tank walls | 4 | Achieving reliable and thorough cleaning of pre-identified waste while maintaining a consistent operational performance throughout the cleaning process. |
| What problems is LANL/DOE currently facing that you think a robotic arm could help solve? | LANL needs to perform more detailed and finer cleaning work that larger equipment cannot reach. | The 6 DoF (degrees of freedom) robotic arms would provide the flexibility that the current equipment lacks, enabling more versatile operations. | The robotic arm must be capable of executing detailed cleaning tasks in areas inaccessible to larger equipment, utilizing its 6 DoF to offer enhanced flexibility and adaptability in operations | 4 | Performing detailed cleaning in confined or complex spaces where larger equipment is ineffective. |

| | | | | | |
|---|---|---|---|---|---|
| What kind of movements would you want to see out of an arm? | A robotic arm with 3 degrees of freedom (DoF) is sufficient, allowing for aiming, vertical movement, and lateral movement with depth control. Additional DoF may be needed for complex geometries. | A simpler design using 3 DoF is preferable, focusing on stable movement within a plane. He recommends a robust arm that can handle larger forces, suggesting that a rod with a brush at the end could accomplish the task effectively. However, he acknowledges that commercially available 6 DoF arms can better adapt to unexpected challenges and complex contours. | The robotic arm should primarily operate with 3 DoF for effective aiming and movement, with the option for 6 DoF to navigate complex geometries and handle unexpected challenges. Stability and the ability to manage larger forces are essential for effective operation. | 3 | Performing controlled movements in a plane with the option for more complex maneuvers. |
| How articulate would the motion have to be? | The articulation of the robotic arm's motion depends on the specific task, such as navigating the curves and ridges of cylindrical tanks. It should be capable of sweeping motions that transition from flat planes to curved surfaces. | The arm needs to follow contours with sweeping motions, effectively flattening the wall while moving along curves and adjusting the distance between the arm and the surface as needed. | The robotic arm must have the ability to articulate its motion for contour following, executing sweeping actions that adapt to both flat and curved surfaces. | 4 | Executing articulate movements to follow the contours of tank walls, transitioning between sweeping motions on flat surfaces, and navigating curves effectively. |

*Appendix C: Supplemental Design Survey Questions*

**Table C-1**: The Supplemental Design Survey asked customers to rate the importance of various Design features for our arm. Survey responses were used to inform the team's ranking of design needs:

| 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? |

*Appendix D: Part Models*

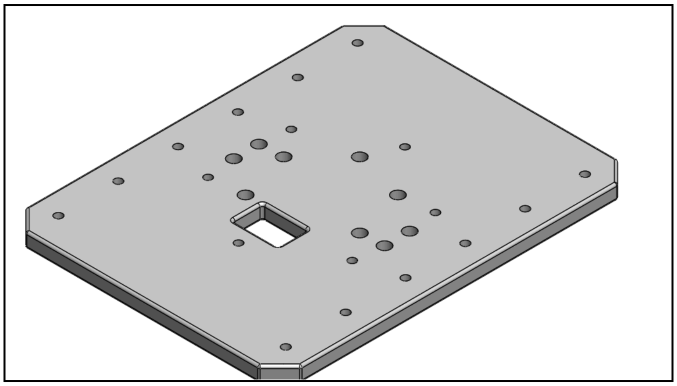


**Figure D-1:** Robot Base

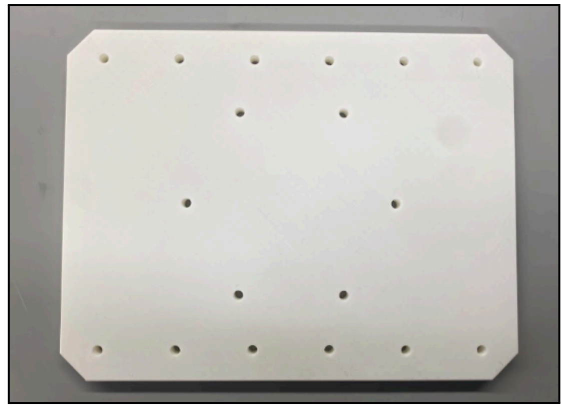


**Figure D-2:** Robot Prototyped Base

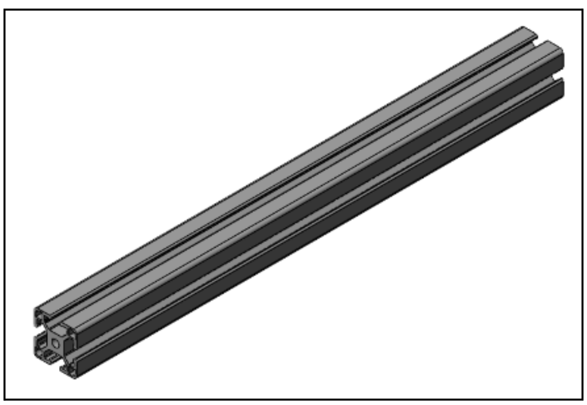


**Figure D-3:** Aluminum Extrusion (6575N202)

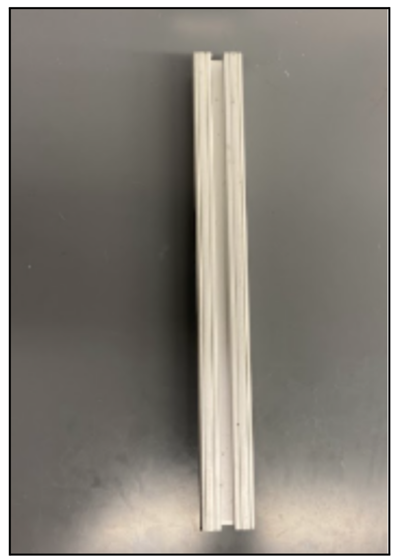


**Figure D-4:** Aluminum Extrusion (6575N202)

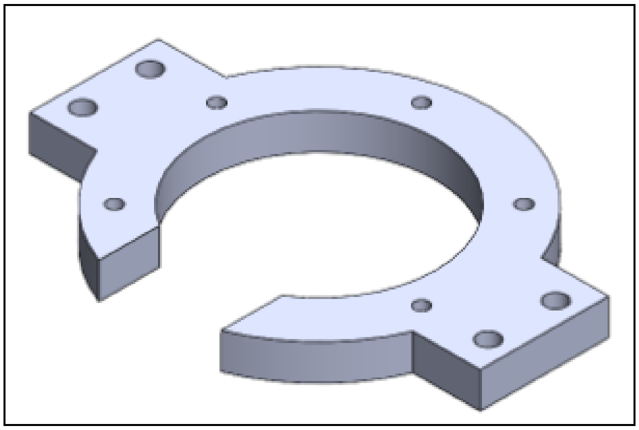


**Figure D-5:** J1 Motor Holder

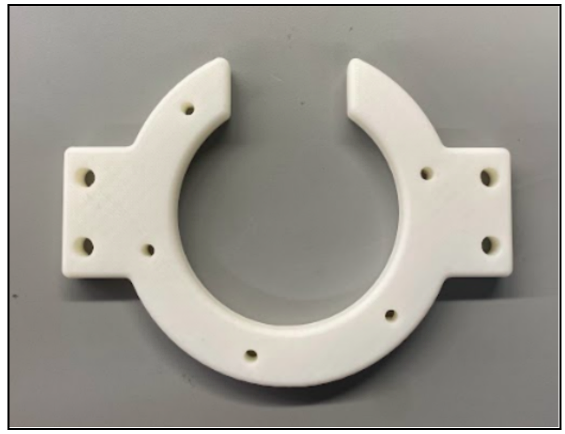


**Figure D-6:** Prototyped J1 Motor Holder

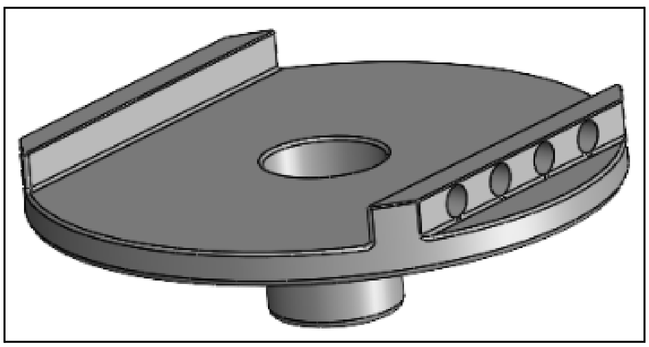


**Figure D-7:** J1 Mushroom Cap

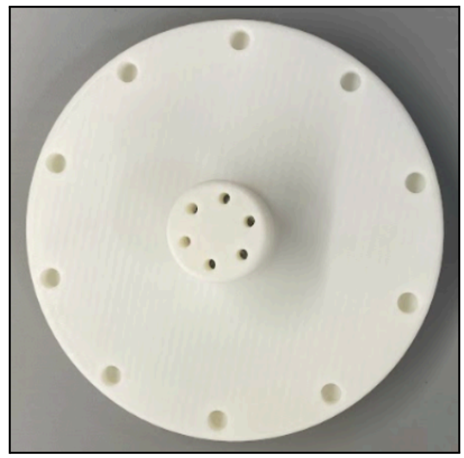


**Figure D-8:** Prototyped J1 Mushroom Cap

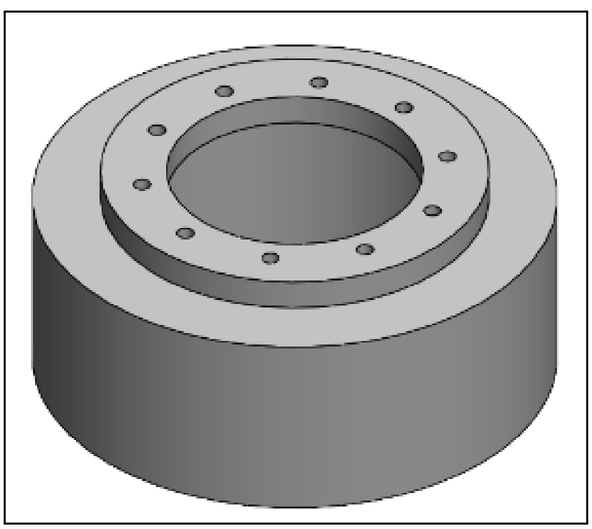


**Figure D-9:** J1 Motor Cover

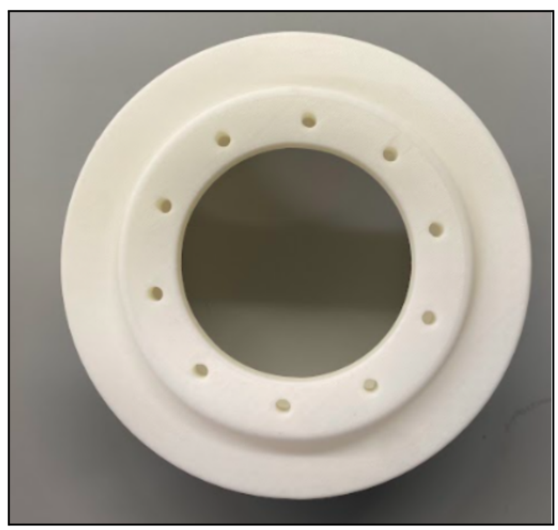


**Figure D-10:** Prototyped J1 Motor Cover

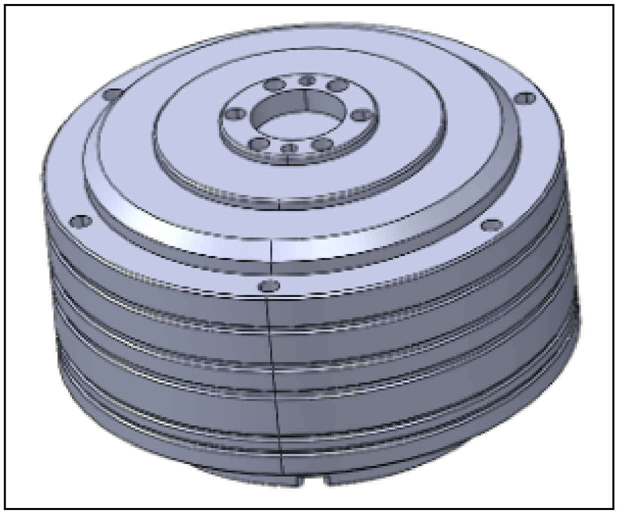


**Figure D-11:** J1 Motor (AK10-9 V2-0)

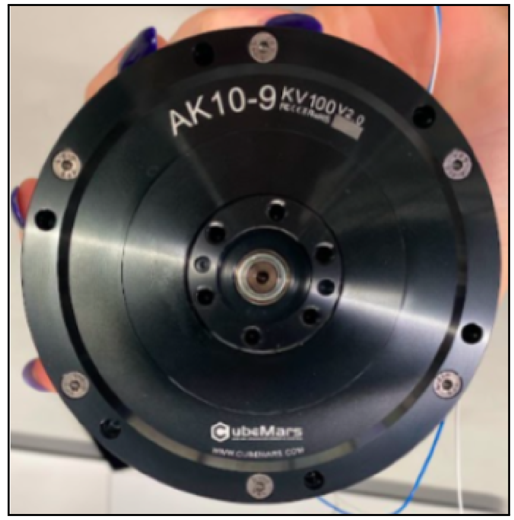



**Figure D-12:** J1 Motor (AK10-9 V2-0)

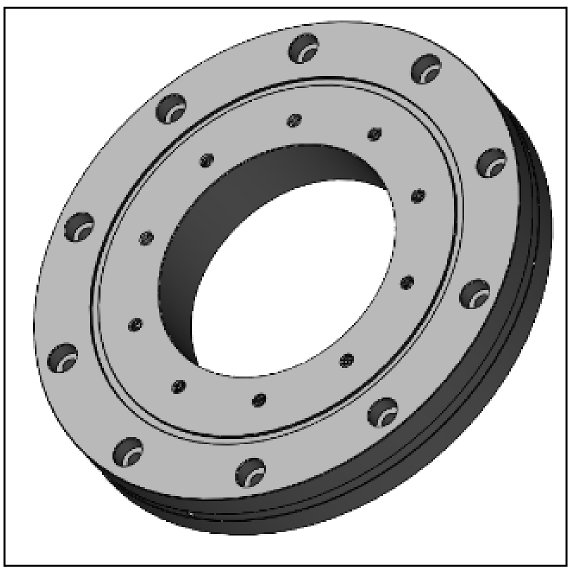


**Figure D-13:** J1 Cross Roller Bearing (2010N16)

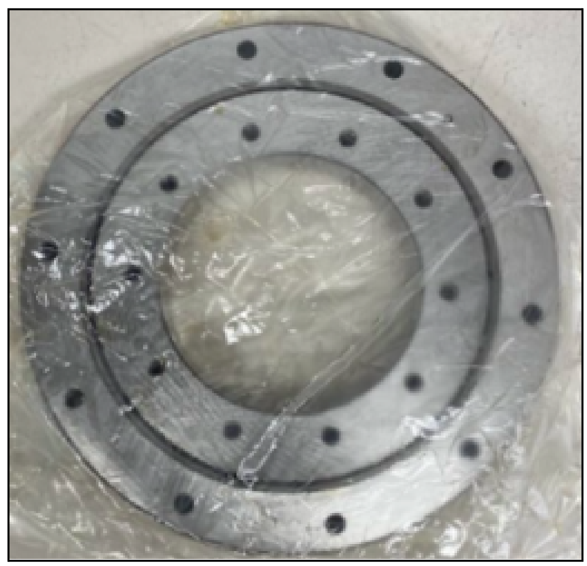
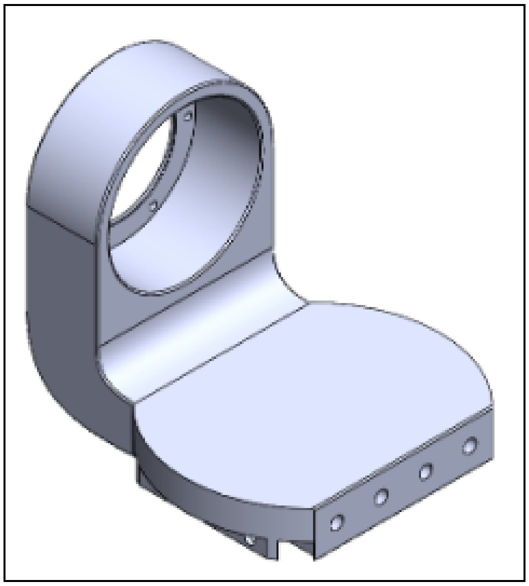


**Figure D-14:** J1 Cross Roller Bearing (2010N16)



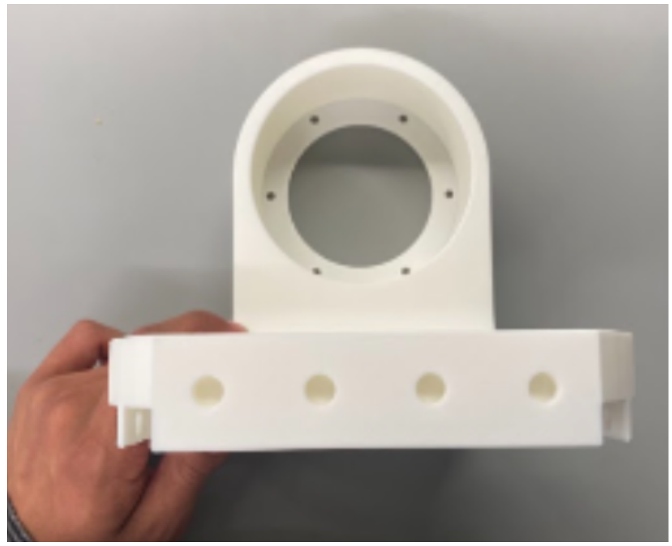
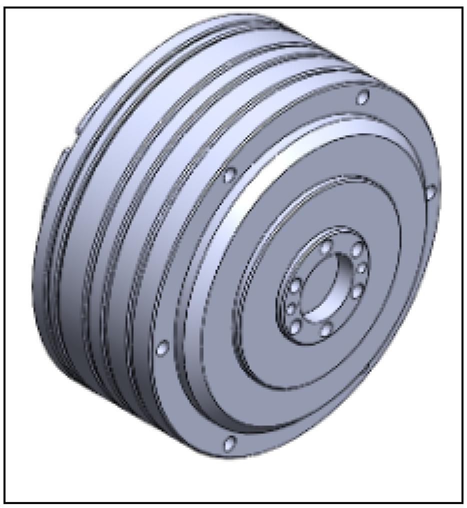


**Figure D-15:** J2 Motor Holder

**Figure D-16:** Prototyped J2 Motor Holder



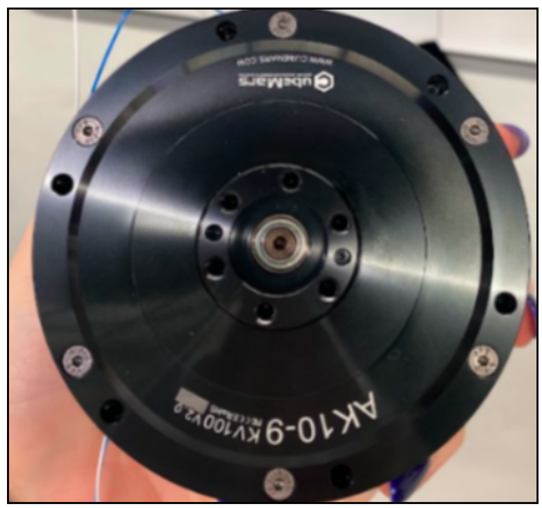



**Figure D-17:** J2 Motor (AK10-9 V2-0)

**Figure D-18:** J2 Motor (AK10-9 V2-0)

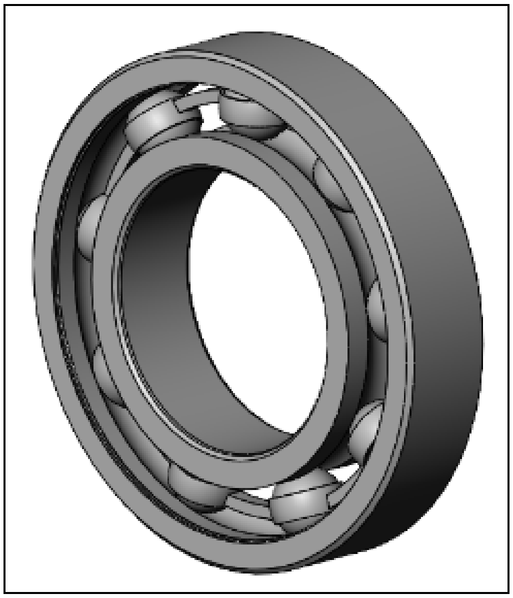


**Figure D-19:** J2 Ball Bearing (K972K3)

**Figure D-20:** J2 Ball Bearing (K972K3)

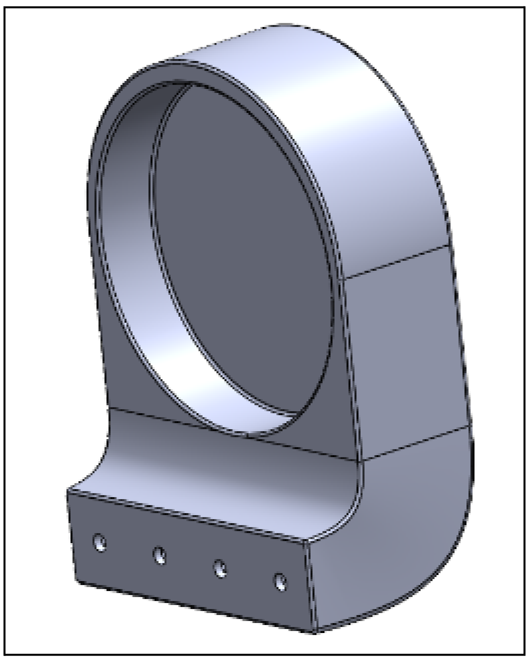


**Figure D-21:** J2 Ball Bearing (K972K3)

**Figure D-22:** J2 Ball Bearing (K972K3)

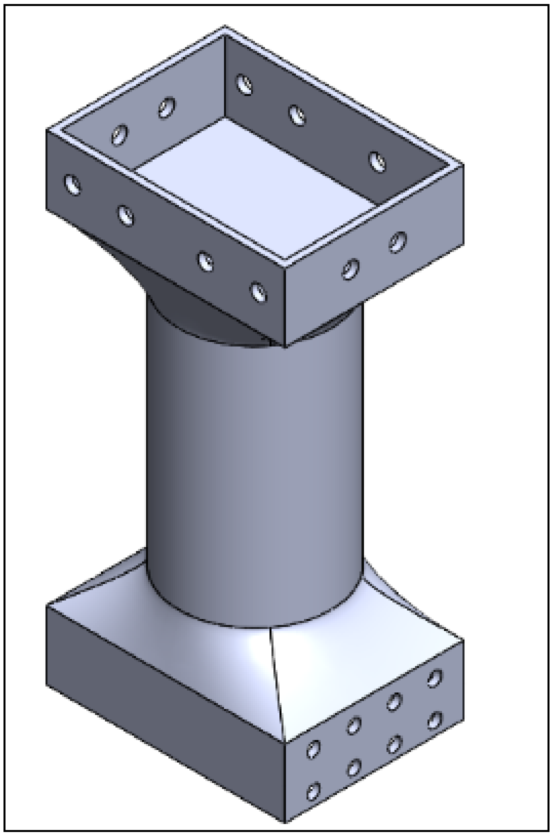


**Figure D-23:** Bicep

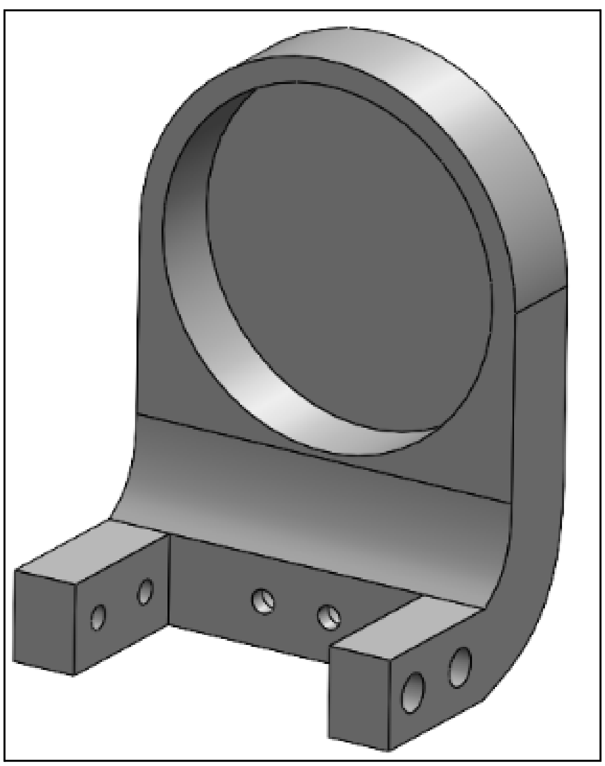


**Figure D-24:** J3 Bearing Holder

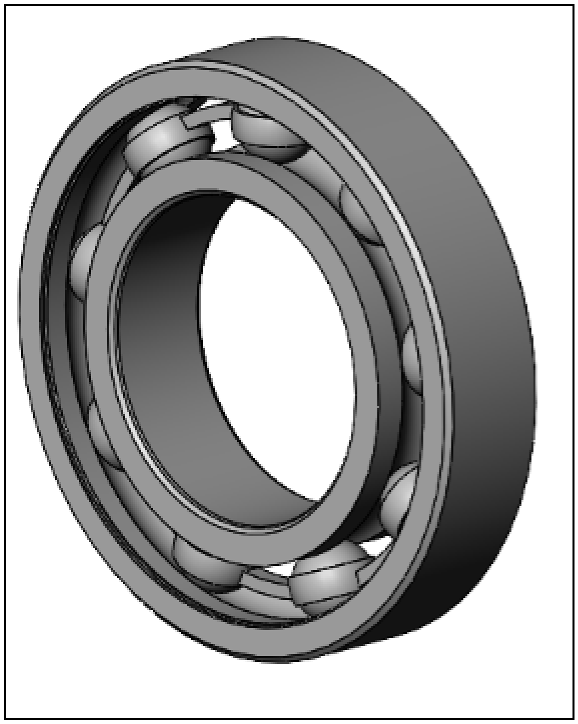


**Figure D-25:** J3 Ball Bearing (5972K113)

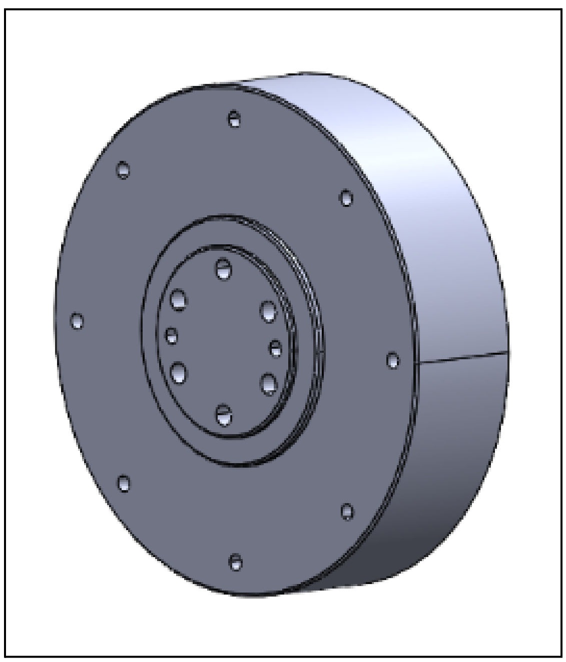


**Figure D-26: J3 Motor** (AK80-6 & AK80-9)

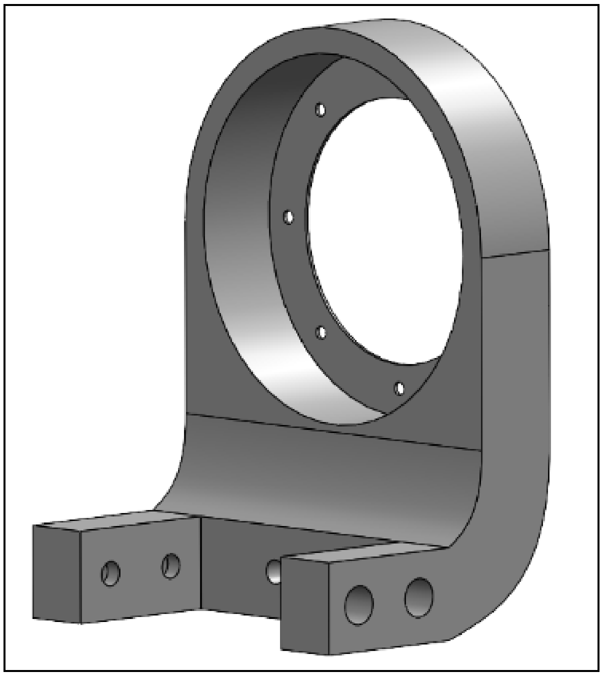


**Figure D-27:** J3 Motor Holder

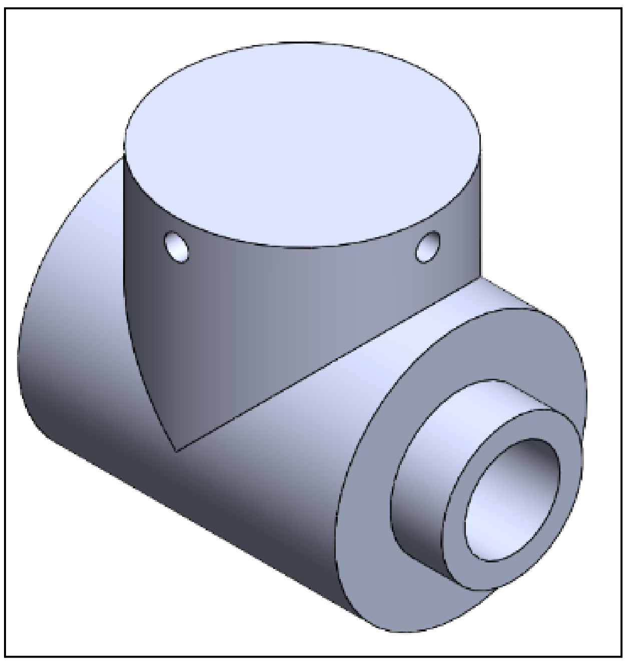


**Figure D-28:** J3 Motor Holder

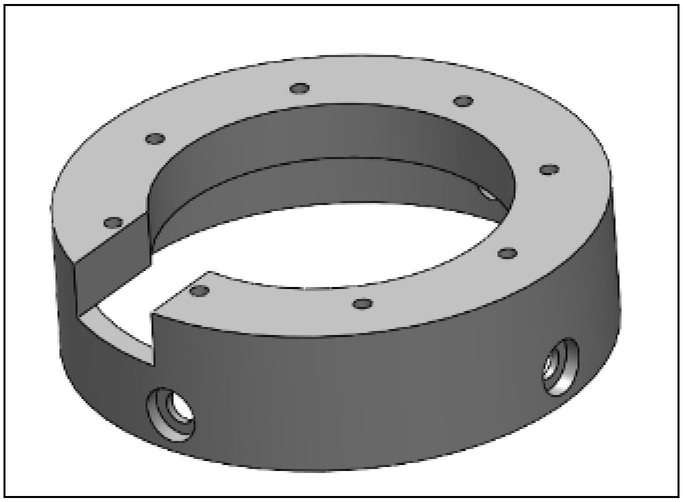


**Figure D-29:** J4 Motor Holder

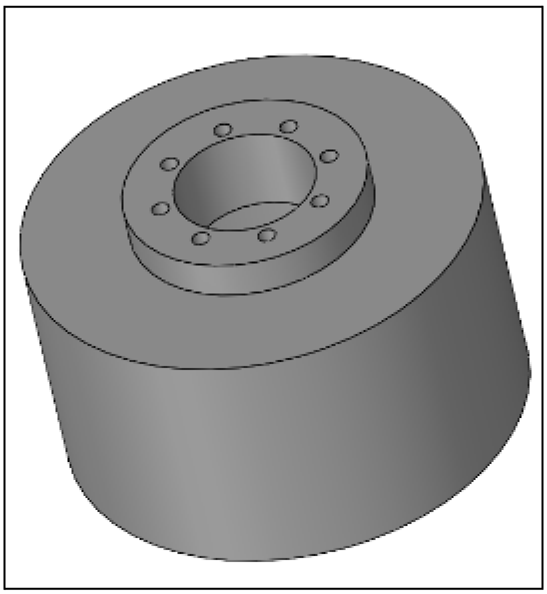


**Figure D-30:** J4 Motor Cover

**Figure D-31:** J4 Cross Roller Bearing (2010N14)

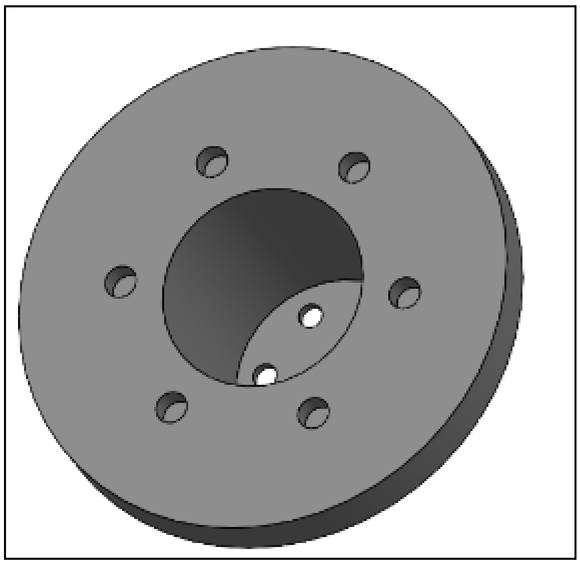


**Figure D-32:** J4 Mushroom Cap

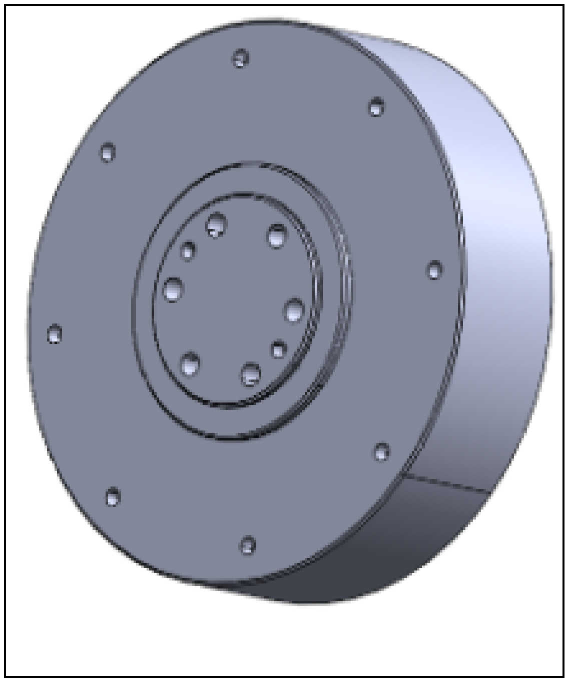


**Figure D-33:** J4 Motor (AK80-6 & AK80-9)

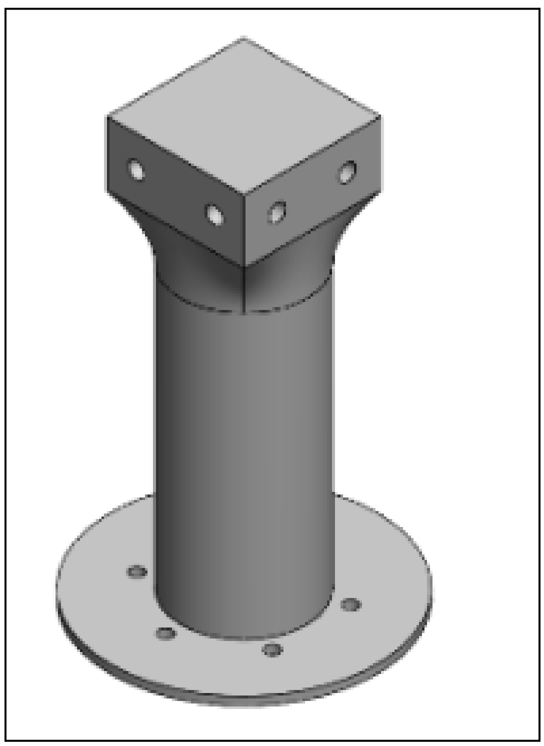


**Figure D-34:** Forearm

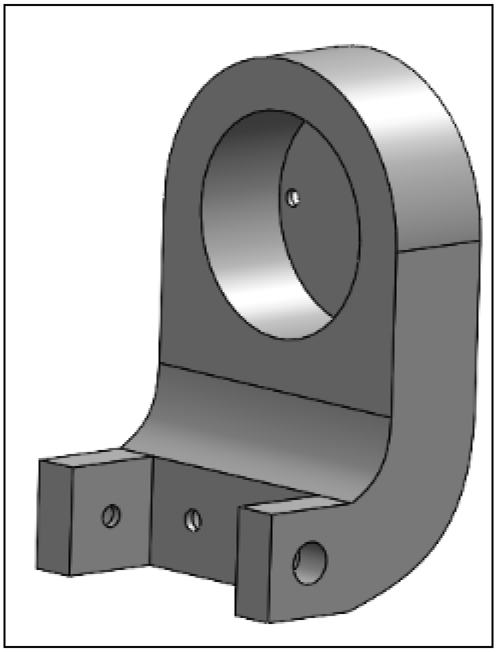


**Figure D-35:** J5 Motor Holder

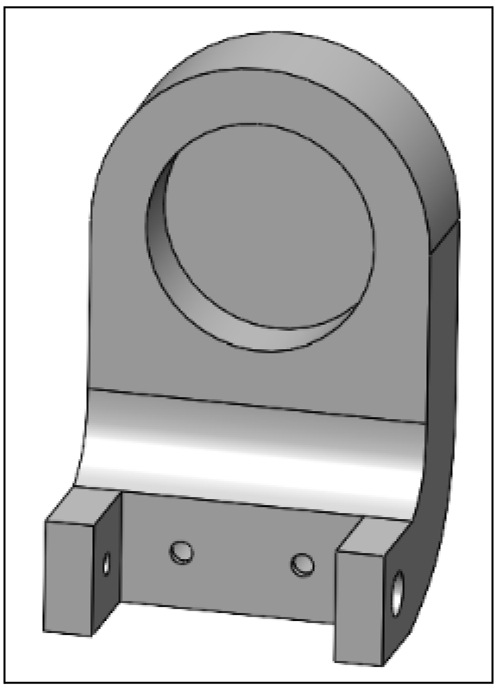


**Figure D-36:** J5 Bearing Holder

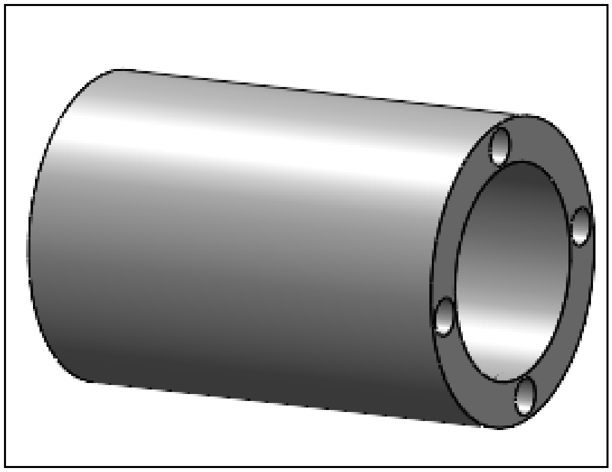


**Figure D-37:** J5 Cylinder

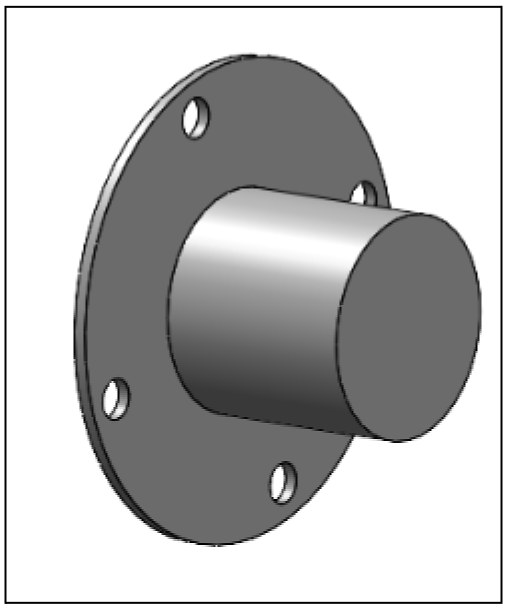


**Figure D-38:** J5 Cylinder Cap

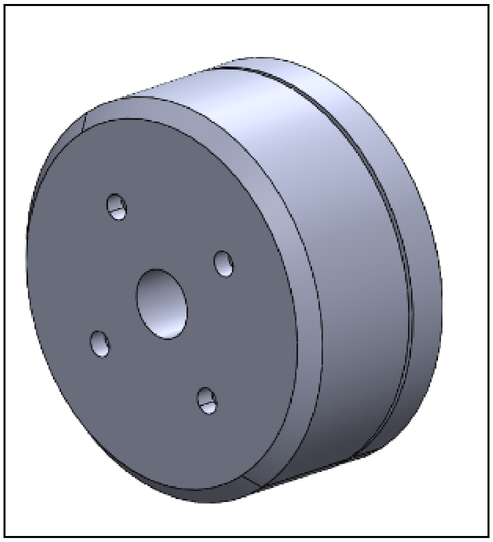


**Figure D-39:** J5 Motor (GL40)

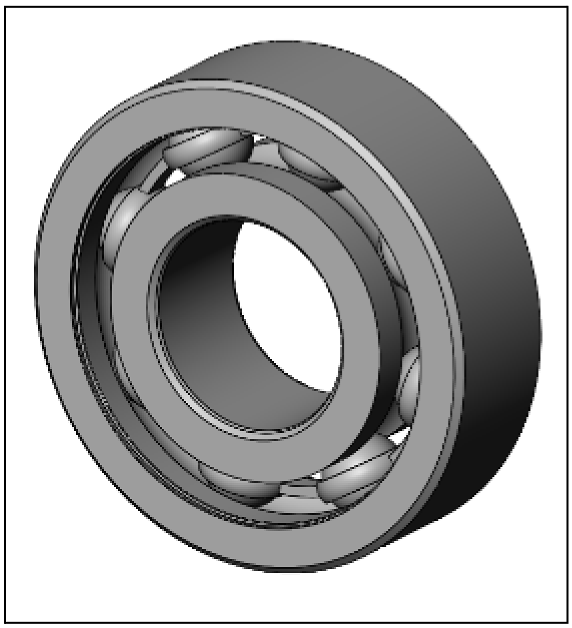


**Figure D-40:** J5 Bearing (5972K105)

| Project Team Name: LANL Human Robotic Arm Capstone | | | | | | |
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| **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?<br>Is the stipulated product architecture and function(s) fulfilled?<br>What auxiliary or supporting functions are needed? | 30% | 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?<br>What disturbing noise factors may be expected?<br>What byproducts may be expected? | 30% | 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<br>minimal performance variance to noise (robustness),<br>adequate durability (strength),<br>efficient material usage (strength to mass ratio),<br>suitable life (fatigue), permissible deformation (stiffness),<br>adequate force flows (interfaces and stress concentrations),<br>adequate stability, impact resistance, freedom from resonance,<br>unimpeded expansion and heat transfer, and acceptable corrosion and wear with the stipulated service life and loads? | 40% | 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),<br>adequate transient and steady state behavior (dynamics and control across energy domains), and appropriate motion, velocity, and acceleration profiles? | 10% | 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,<br>operation, and the environment been taken into account? | 80% | 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 |
| **Ergonomics** | Have the human.. machine relationships been fully considered?<br>Have unnecessary human stress or injurious factors been predicted and avoided?<br>Has attention been paid to aesthetics and the intrinsic "feel" of the product? | 100% | The team has come together to design and implement a safety cage for our manipulator. This has been created to accommodate for failures in our design that could lead to human injury. Furthermore, for our specific design the manipulator will have a sleek design of preferably all one color PLA, as well as curved edges to meet aesthetic requirements. | None | Dalton Boeckmann | February 3, 2025 |
| **Production** | Has there been a technological and economic analysis of the production<br>processes, capability, and suppliers? | 50% | Yes, the team. has worked closely with vendors to ensure the economical side of our production has been accounted for and tabulated in our BOM. Furthermore, on the technical side the team has been working closely with LANL and other Professional Engineers to ensure the technical feasibility of our design, and to ensure it will work. | The team hasn't been able to test the motors yet due to technical challenges with finding a power supply, and connecting to it with the motors. This has led the team to push back any technical issues they might have with the control of the robotic joints. | Dalton Boeckmann | March 1, 2025 |
| **Quality Control** | Have standard product tolerances been chosen (not too tight)?<br>Have the necessary quality checks been chosen (type, measurements, and time)? | 60% | We have already run into issues with hole sizes in solidworks vs the PLA printed prototype. We have talked with the RPS and have decided that we will increase the size of the holes in Solidworks to make up for this tolerance issue. So far the holes have been smaller than anticipated. Other than that the quality of the motors and bearings seem good. | We have an issue with the mushroom cap we designed for J1. If it is not interfacing well with the motor and bearing once we receive fasteners, then I will change the dimensions of this part to resolve that issue. | Jade | Feb 15, 2025 |
| **Assembly** | Can all internal and external assembly operations be performed simply, repeatedly, and in the correct order (without ambiguity)?<br>Can components be combined (minimize part count) without affecting modular<br>architectures and functional independence of the product? | 5% | Assembly operations have not been performed yet. We will begin this step once we receive fasteners from McMaster-Carr. However, half of the prototyping has been completed so that assembly can begin promptly. We hope that assembly will be simple, although our arm has a lot of components so we do expect it to be long. Components cannot really be combined without affecting modular architectures at this stage. | As we have not fully began assembly, it's possible for issues to come about. | If assembly is proving difficult we will look back at the design and look at what we can change/improve to fix it. Jade | March 1, 2025 |
| **Transport** | Have the internal and external transport conditions and risks been identified and<br>solved?<br>Have the required packaging and dunnage been designed? | 90% | Yes, the team has considered that transportability in the design process for both external and internal components. All Internal components will be secured together with allocated fasteners as well as press fittings with the correct tolerancing, allocated by our CAD team. As for external components, the manipulator will be attached to two T-Slot Aluminium Extrusions and a PLA Base that will offer for sleek and easy transportability. | The only issue that would impede on the teams design for transportability would be the prospected safety cage that has be allocated by our sponsor, due to its size and shape it may be hard to transport this aspect of the teams design. | Mitigation Strategies: Assemble and Disassemble Safety Cage when transporting and or create an easy step by step plan for when transporting manipulator Persons: Dalton Boeckmann and Morgan Gullo | March 1, 2025 |

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| **Operation** | Have all of the factors influencing the product's operation, such as noise,<br>vibration, and handling, been considered? | 40% | The team has considered vibrational and electrical noise that will come from our motors, this has been accounted for noise reducers in electrical wiring as well as accounting for physical vibration with fasteners in critical areas. | Certain Issues have not been discovered as of right now because the team hasn't finished manufacturing the robot, but the team anticipates that when the robot is manufactured and powered on there will be vibrational effects from the motors, and this will need to be mitigated. | Mitigation Strategies: Redesign of Pieces affected by Vibrational Effects, Implementation of more Noise Reducers in Electrical Wiring Persons:Dalton Boeckmann and Jade Waldron | March 1, 2025 |
| **Lifecycle** | Can the product, its components, its packaging be reused or recycled?<br>Have the materials been chosen and clumped to aid recycling?<br>Is the product easily disassembled? | 90% | As far as recycling, our prototype is made out of PLA which can be recycled. But the 3D printed parts are made specifically for our arm so it would be very difficult to integrate them into a different design. Also, our team has designed our arm around the specific motors we picked out so it would also be very difficult to change the type of motors in the future. Our design can be disassembled and the motors can be reused for other projects. | In the future, we potentially plan to make the arm out of a stronger material which could not be recyclable. Also, our design includes many types of fasteners which could complicate assembly and the potential use of the individual fasteners. | Mitigation Strategies: Redesign holes to allow for limited variations of fasteners. Build with a material that can be recycled/reused, integrate assemble steps or make design more integral (Jade Waldron and Dalton Boeckmann) | March 1, 2025 |
| **Maintenance** | Can maintenance, inspection, repair, and overhaul be easily performed and<br>checked?<br>What features have been added to the product to aid in maintenance? | 50% | Since having a more modular design, it will be less difficult to perform maintenance, inspections, and repairs. This is because the team will be able to access certain points within our design by removing the necessary fasteners to access the needed portion. Our team designed our arm with the expectation of testing it as the assembly was made. | Although maintenance will be easily accessible, many repairs will be difficult to be made since the majority of our parts are made from PLA and repairs would require our team to completely reprint the part. | Mitigation Strategies: Perform maintenance as assembly is made and be aware of obstructing parts before performing any motion in the arm. Incorporate easy accessibility near motors (Entire team) | February 21, 2025 |
| **Costs** | Have the stipulated cost limits been observed?<br>Will additional operational or subsidiary costs arise? | 65% | Through previous budgeting, our team planned to spend within the allotted $5000 with an 80% margin. Throughout the beginning of this semester, many additional costs have be added including unexpected customs cost. With the additional costs, our team was forced to reach out to our sponsor to aid us on purchasing the more expensive items. Our team is still needing to purchase electrical components, but with our sponsor picking up the larger costs, there is now more room in the budget for the remaining items. | Our team is waiting to hear back from our sponsor to see if he is able to purchase the remaining motors needed as well as the power supply needed to power our robotic arm. We also are waiting to see if there will be enough money to improve our filament to a stronger material to provide a more suitable protype for its potential use. | Mitigation Strategies: Our team plans to continue to document each purchase and keep track of what has been spent and the remaining amount of money that can be used. We are also in constant contact with our sponsor to let him know the status of our purchases and way he can provide aid. (Morgan) | February 14, 2025 |
| **Schedules** | Can the delivery dates be met, including tooling?<br>What design modifications might reduce cycle time and improve delivery? | 70% | Most of the items with the longest delivery time have been purchased and delivered. The remaining items needed have a much shorter delivery time and should arrive in a timely manner. As far as prototyping, the physical model is on track but the most time consuming will be programming the robotic arm. We also want to try to use extra items that have been collected from past capstone groups to limit the time spent on ordering and delivering the items. | Our team is waiting on our final 2 motors and power supply from our sponsor which have set back our schedule. We are still waiting to purchase the rest of the electrical components but using amazon as our vendor should not account for a long delivery time. | Mitigation Strategies: Our team is trying to order all of our needed items as soon as possible and is in constant contact with our sponsor and studio instructor to have items approved and ordered in a timely manner. We have also been in contact with the head purchase ordering individual which has helped keep things on track. (Morgan) | February 14, 2025 |

*Appendix F: Complete FMECA*

| | | Assessment | | | | | | | Recommended Actions | |
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| **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 |
| 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 |