MEEN 402 INTERMEDIATE DESIGN; SECTION 502
April 29, 2025

FINAL REPORT

TEXAS A&M UNIVERSITY

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Human Robotic Arm Attachment

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, in collaboration with Dr. David Mascarenas from Los Alamos National Laboratory, are designing a robotic arm attachment to address a critical cleaning challenge within nuclear waste facilities. This project aims to improve remote handling of hazardous materials by eventually mounting a five degree-of-freedom (5 DoF) robotic arm onto the Boston Dynamics Spot robot—a four-legged, dog-sized, mobile platform known for its agility and ability to navigate challenging environments autonomously or via remote control. The arm is designed to clean radioactive waste residues to minimize contamination risks without direct human intervention.

The project arose from known limitations in accessibility and safety within nuclear waste facilities identified during discussions with professionals at 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. After a full semester of planning, sketching, and defining all necessary components, the team transitioned into the build phase, purchasing, fabricating, and assembling parts over the current semester. This robot now receives inputs from a computer, with a primary focus on achieving a functional frequency of at least 1 Hz, meaning each joint of the arm can reliably complete at least one full movement cycle (rotation or extension) per second. This benchmark ensures the system will maintain sufficient speed and responsiveness for real-time control under various operating conditions.

To guide development, the team conducted preliminary research, expert interviews with Savannah River National Laboratory, and a supplemental design survey to understand user needs. Critical features identified included maneuverability, lightweight construction, and quick response times. Survey responses also highlighted concerns about overall stability and weight distribution when mounted on a quadruped robot, prompting the team to keep the center of gravity low. While precision remains relevant, speed and versatility emerged as higher priorities given the operational context and customer expectations. The full assembly is shown in **Figure E1**, with an approximate reach of 1 meter when fully extended; detailed dimensions are discussed later in the report.

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.

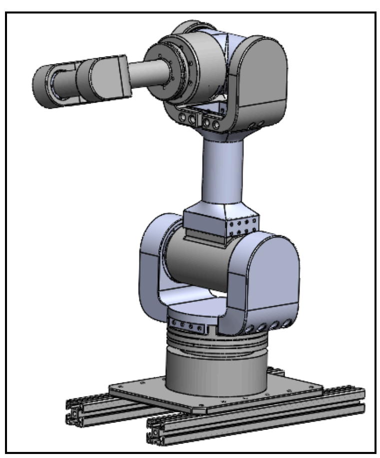

Figure E1: Final CAD Assembly

Table of Contents

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 waste. 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 the 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 four degrees-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 as 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 Team's 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 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 in 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**). The base and aluminum extrusions holding the robot up are not a part of a specific subassembly. But they can be seen below in **Figure 1**.

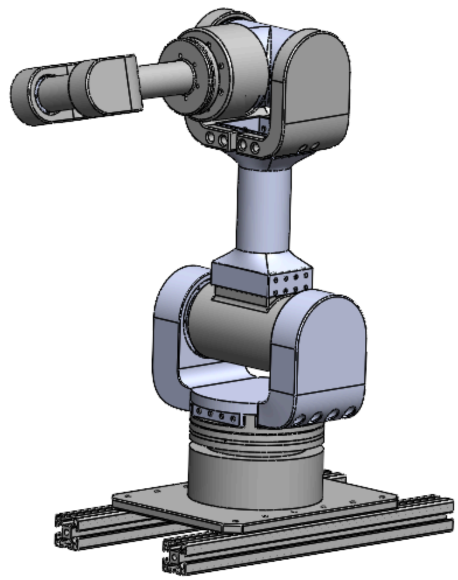

Figure 1: Final CAD Assembly

2.1. Joint 1 (J1) Subassembly

Figures 2 and **3** below show 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** (Figures D-5 to D-14)**.** The Engineering Drawings, including specific dimensions of each individual part, can be found in **Appendix E** (Figures E-2 to E-6). The size of J1 ranges depending on the part being analyzed, however, it is about 165 mm in diameter for reference (refer to **Appendix E**). 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 that 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.

J1 was challenging to design as there were a lot of parts that needed to be considered for it to function effectively. For example, we noticed after prototyping the J1 Mushroom Cap that the bearing was going to rub onto the PLA part and generate a lot of friction, especially with all of the added weight of the arm. So we added a divot that was the exact size of the inner ring of the bearing to prevent this from happening (Appendix E, Figure E-3). It was minor tweaks like this in our design that made J1 particularly time-consuming. After fixing this, we made sure not to make the same mistake in other joints, especially J4.

There are a variety of holes in this subassembly, ranging from M4 to 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.

Additionally, we failed to realize that not making counterbored holes in J1 would be difficult for us later on. When J1 was prototyped, and we tried to assemble it to the base, we realized that all 6 fasteners on the J1 Motor Cover were sticking out and would not allow for the Base to be assembled to J1. So, to combat this problem, a new base was created to allow these fasteners to stick out. We considered counterboring the holes for J1, however, this would be extremely time-consuming, as we would have to redo heat-set inserts and also find new fastener lengths to suit the new dimensions. This is why J1 has fewer counterbored holes than the rest of the robotic arm. Because of this, we decided to counterbore more holes as we refined the design for the rest of the joints.

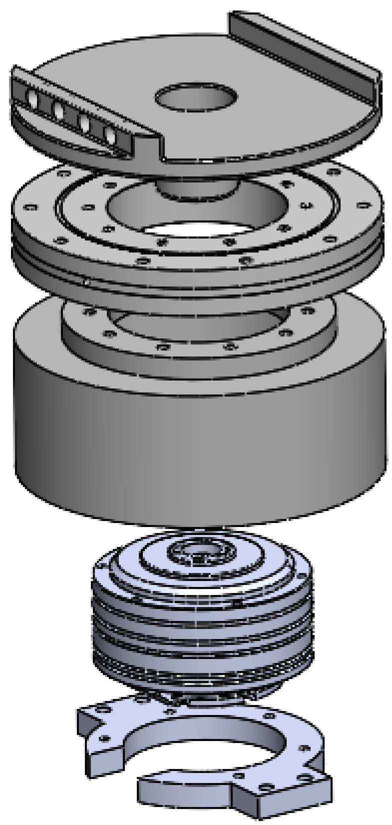

Figure 2: J1 Assembly

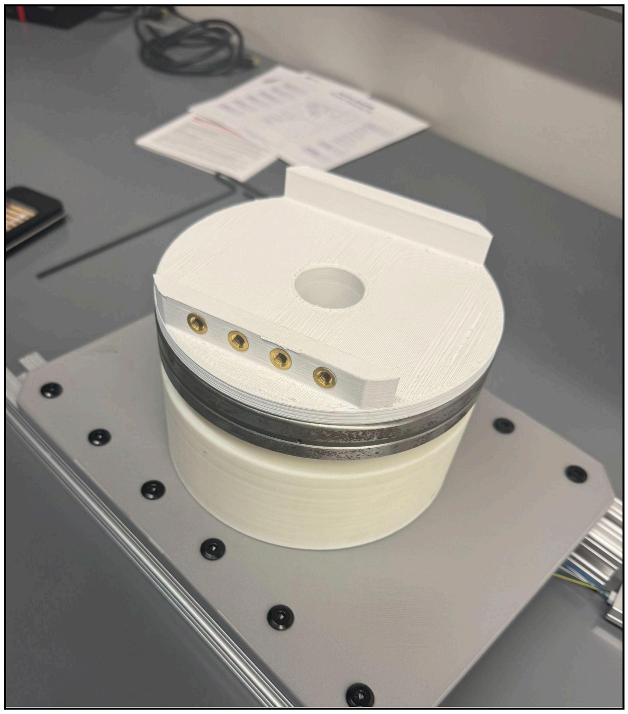

Figure 3: Prototyped J1 Assembly

2.2. Joint 2 (J2) Subassembly

The J2 assembly features a different design from 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. Initial designs of J2 last in MEEN 401 failed because J2 was much larger than J1 in size. Our current design ensures that the Motor Holder of J2 is the same diameter as the J1 Mushroom Cap (~165 mm). **Figures 4** and **5** below show the motor and bearing on opposite sides of a cylinder that allows for their connection. This configuration is necessary for movement, but it also balances the weight of J2.

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 of each component can be found in **Appendix D** (Figures D-15 to D-24)**.** The Engineering Drawings, including specific dimensions of each individual part, can be found in **Appendix E** (Figures E-6 to E-10). The J2 Assembly is around ~230 mm in length at its widest point. Close tolerances of ~1 mm were used to press fit the bearing into the bearing holders, but also into the cylinders as well. When the tolerance was too large (>1 mm), the bearing or inner ring would not press-fit and would be loose, resulting in an unusable part. This was especially important in all of our ball bearings (J2, J3, J5). **Figures 4** and **5** show the construction of every component up to the Bicep linkage.

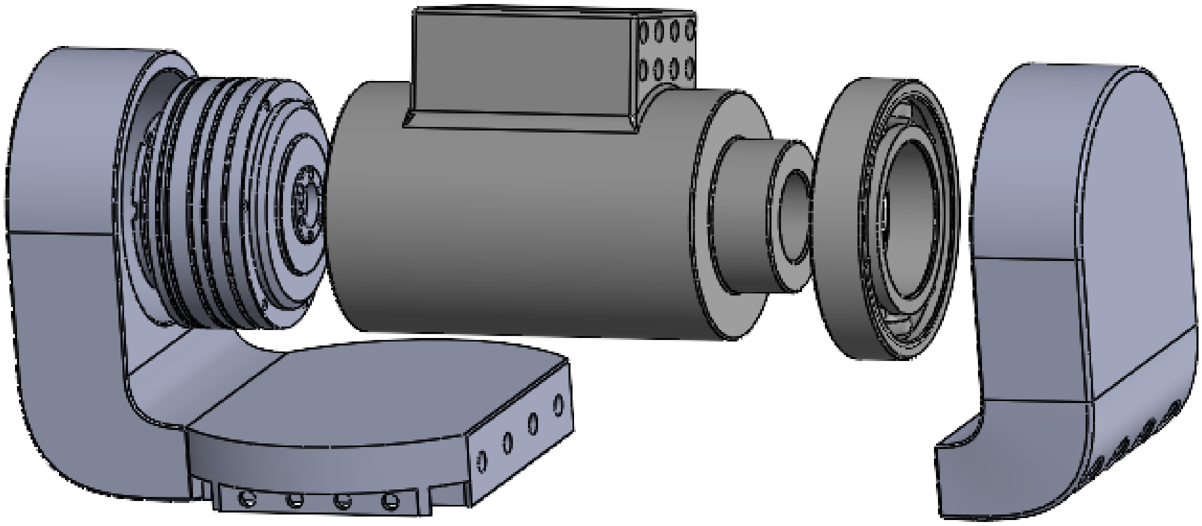

Figure 4: J2 Assembly

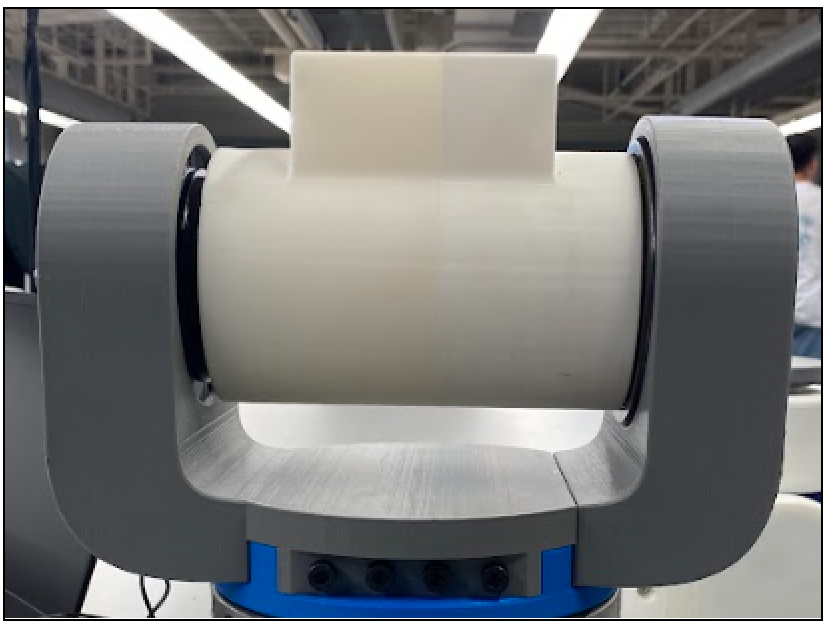

Figure 5: Prototyped J2 Assembly

2.3. Joint 3 (J3) Subassembly

The J3 Assembly, seen in **Figures 6** and **7,** 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. The individual pictures of each component can be found in **Appendix D** (Figures D-25 to D-36)**.** The Engineering Drawings, including specific dimensions of each individual part, can be found in **Appendix E** (Figures E-11 to E-16). 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. The J2 assembly is around ~150 mm at its widest point. **Figure 7** shows the prototyped J3 Assembly.

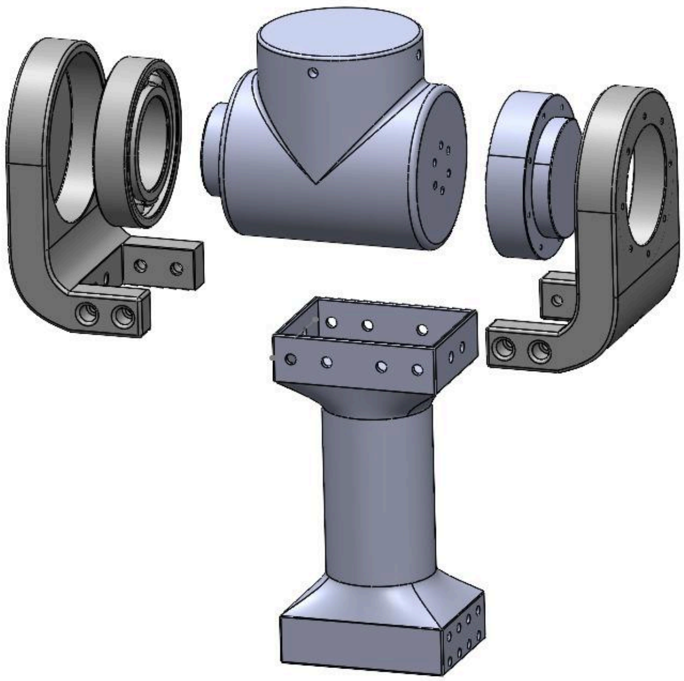

Figure 6: J3 Assembly

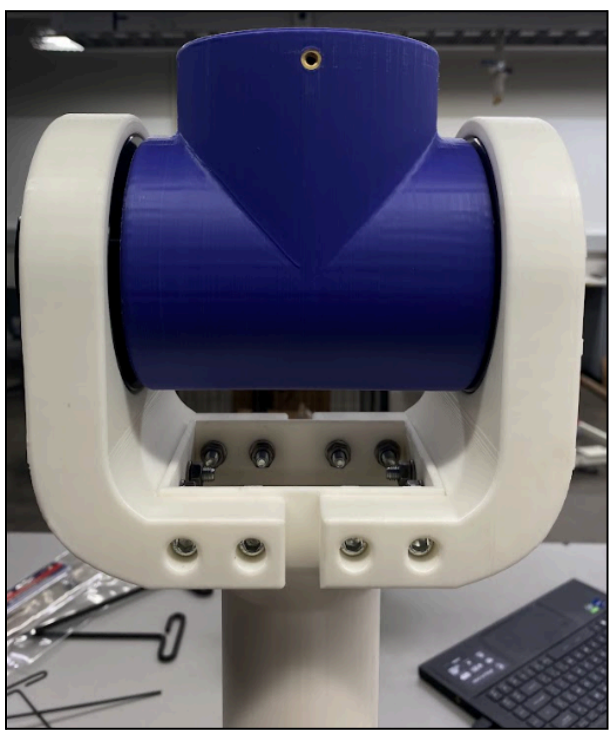

Figure 7: Prototyped J3 Assembly

2.4. J4 Subassembly

The J4 assembly shown in **Figure 8** 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 individual pictures of each component can be found in **Appendix D** (Figures D-37 to D-44)**.** The Engineering Drawings, including specific dimensions of each individual part, can be found in **Appendix E** (Figures E-14, E-17 to E-20). The J4 assembly is around ~95 mm at its widest point. 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 9** shows the prototyped J4 Assembly.

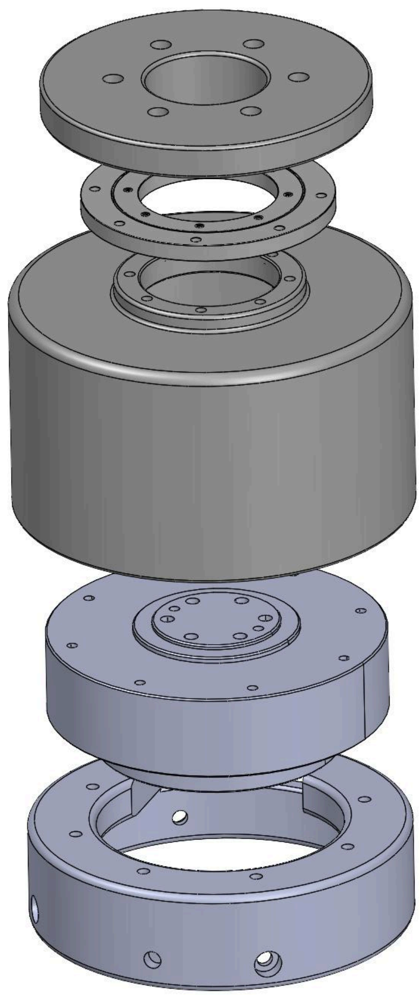

Figure 8: J4 Assembly

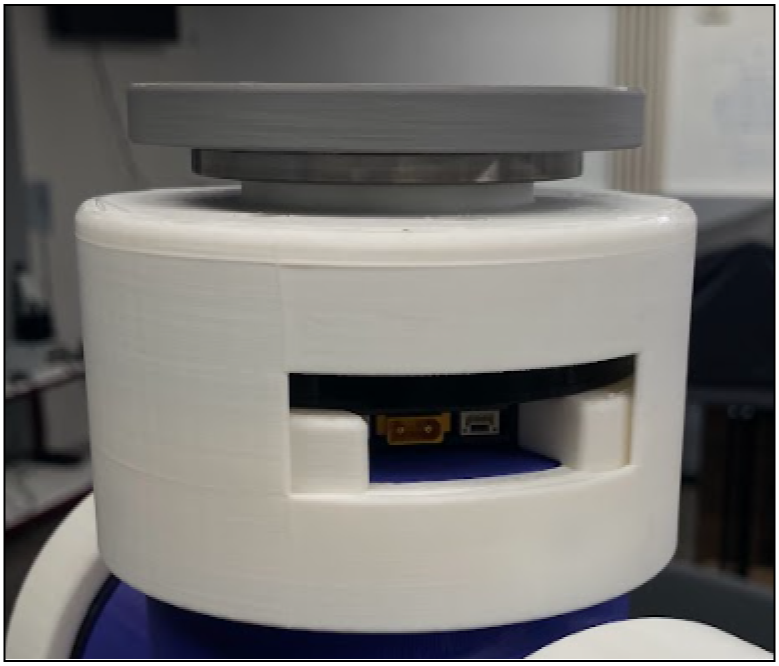

Figure 9: Prototyped J4 Assembly

2.5. J5 Subassembly

The J5 assembly can be seen below in **Figure 10**. 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 individual pictures of each component can be found in **Appendix D** (Figures D-45 to D-60)**.** The Engineering Drawings, including specific dimensions of each individual part, can be found in **Appendix E** (Figures E-21 to E-27). 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. The J5 assembly is around ~140 mm at its widest point. **Figure 11** shows the prototyped J5 Assembly.

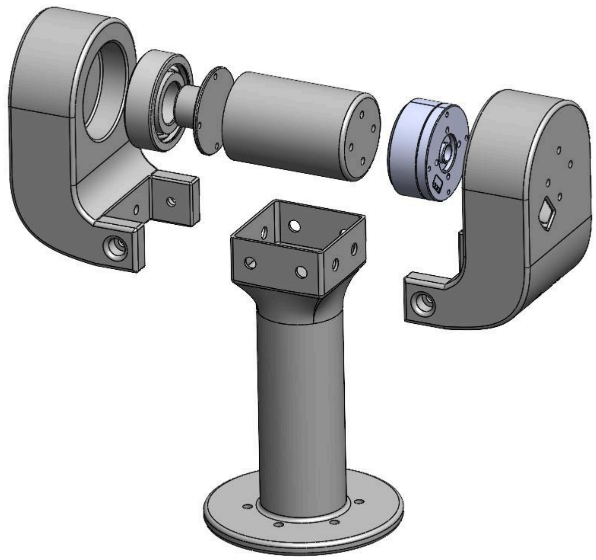

Figure 10: J5 Assembly

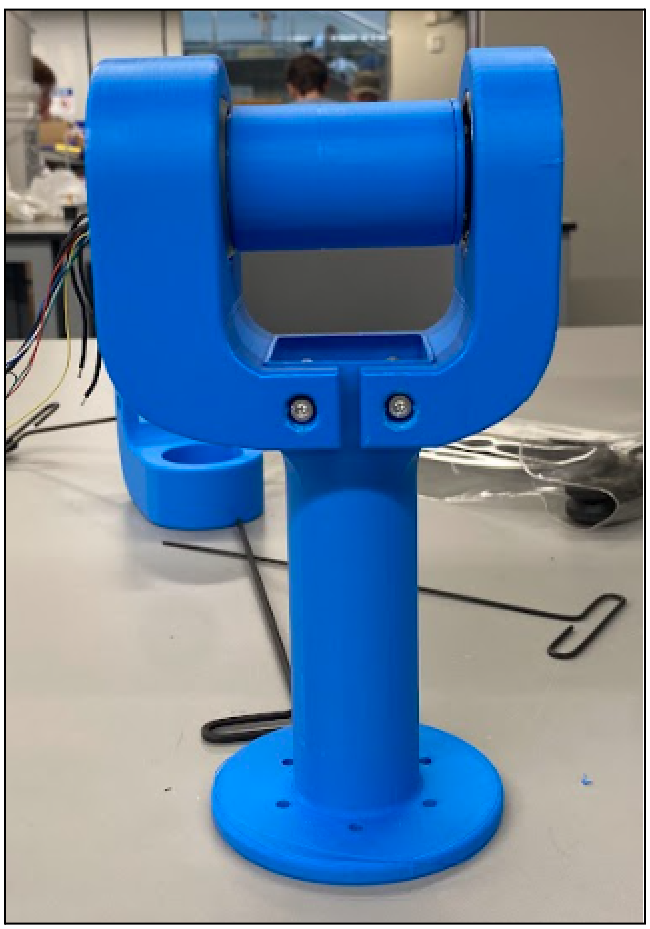

Figure 11: Prototyped J5 Assembly

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 next prototype, ASA and PETG are the better option since they are stronger, more flexible, and resistant to heat and impact, which means the arm will hold up better under real-world conditions. Unlike PLA, PETG/ASA won't become brittle over time or warp if it gets too warm. Using PLA for prototyping and PETG/ASA for the next prototype strikes the right balance between fast, cost-effective development and long-term durability. Due to the sheer number of parts in our robotic arm, the team has included all pictures of the PLA 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

2.8.1. Controls Interface

To control the brushless DC motor, the team selected a serial-to-USB interface device known as the "R-Link," provided by CubeMars, the same vendor from which the motors were purchased. The R-Link facilitates communication between the motor and a computer, with the serial end connected to the motor and the USB end connected to the computer. The setup illustrating the connection between the motors and the R-Link is shown below:

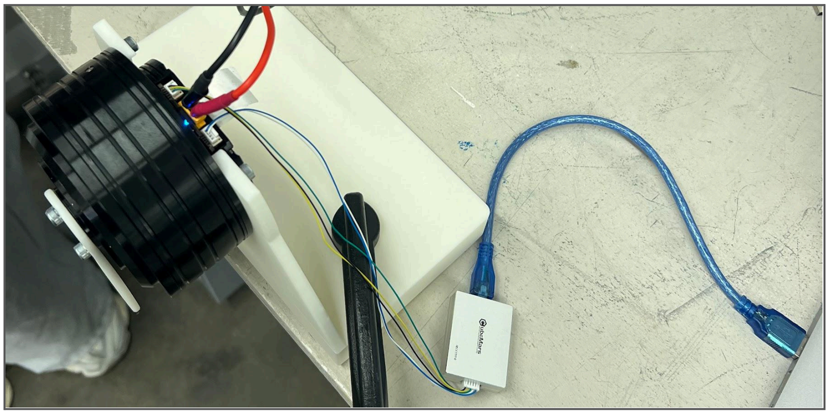

Figure 10. R-Link Controls Interface

The R-Link enabled the team to interface with a control software known as the "Upper Computer" (**Figure 11**). This software provided functionality to command and test each motor's position, speed, and torque, as well as to fine-tune the proportional (Kp) and derivative (Kd) control parameters. Using the Upper Computer, the team successfully achieved individual control of all motors. However, the software does not support simultaneous multi-motor control, requiring a separate R-Link device for each motor.

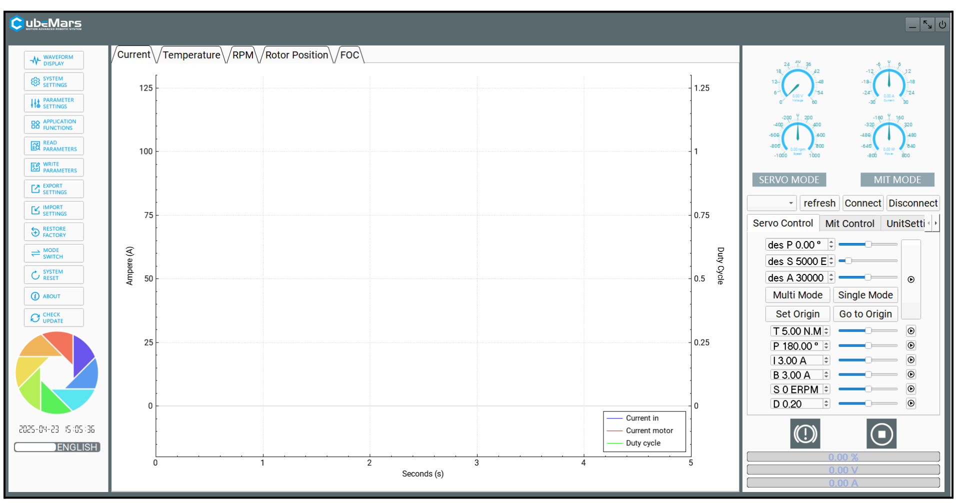

Figure 11. Terminal Block Setup

2.8.2. Wiring Interface

The wiring interface for the robotic arm was carefully designed to meet the power and connectivity requirements of the five motors integrated within the system. To ensure the electrical setup was safe and reliable, the team reached out to Dr. Lusher, an electrical engineering professor at Texas A&M, who guided key decisions. A power supply from B&K Precision (80V, 60A) was provided by the sponsor after the team created a wiring diagram based on the motors' total current demands. The power supply contained ring terminals, so a heavy-duty battery cable was used to connect its positive and negative terminals to two separate terminal blocks—one for the negative side and one for the positive side. From the terminal blocks, four wires were used, each with an O-ring terminal on one end (to connect to the terminal blocks) and an XT60 connector on the other. Since each motor required an XT30 connection, XT60-to-XT30 adapters were purchased to complete the connection to each motor. The team used mesh sleeves to bundle the wiring and maintain a clean and organized layout. Future improvements to the wiring system could include purchasing dedicated jumpers for the terminal blocks to further the usability of the system.

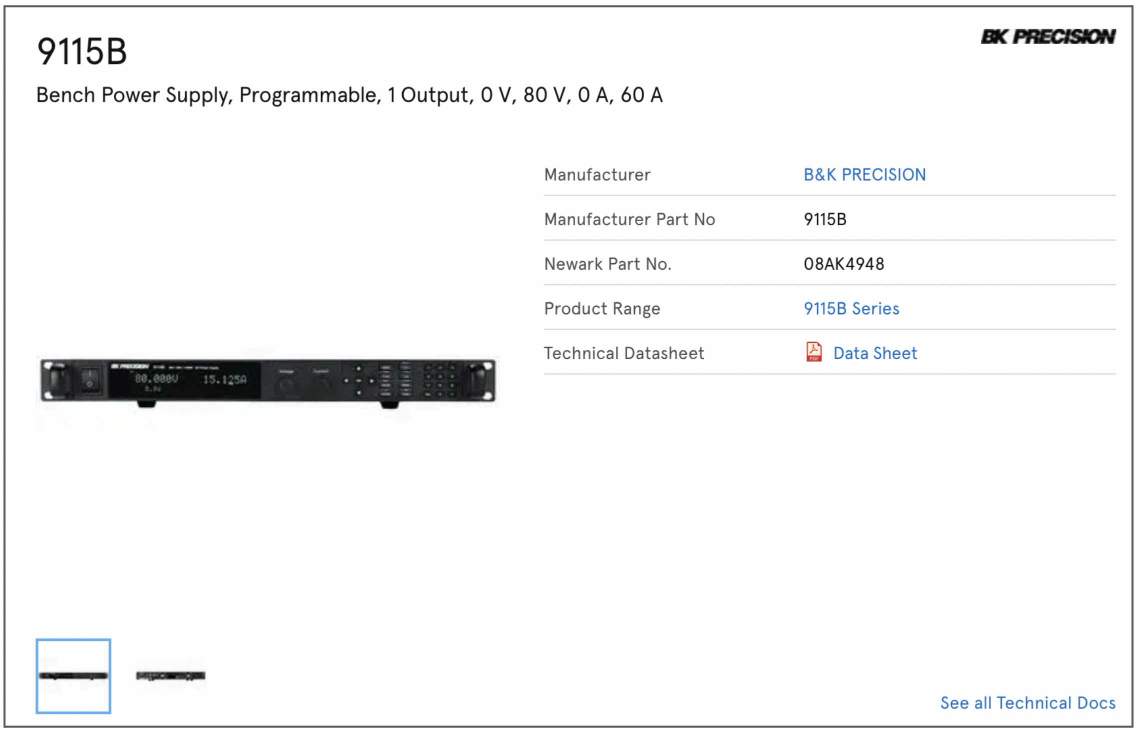

Figure 12. B&K Precision Power Supply

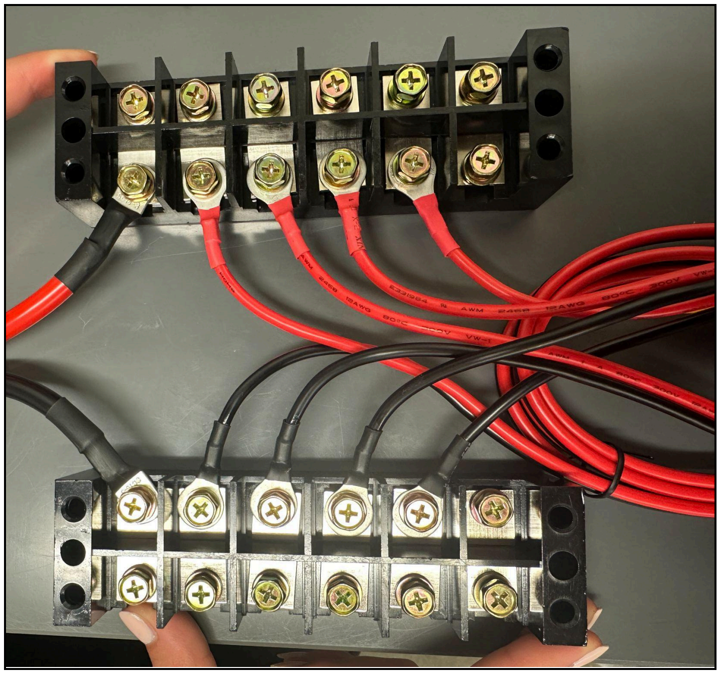

Figure 13. Terminal Block Setup

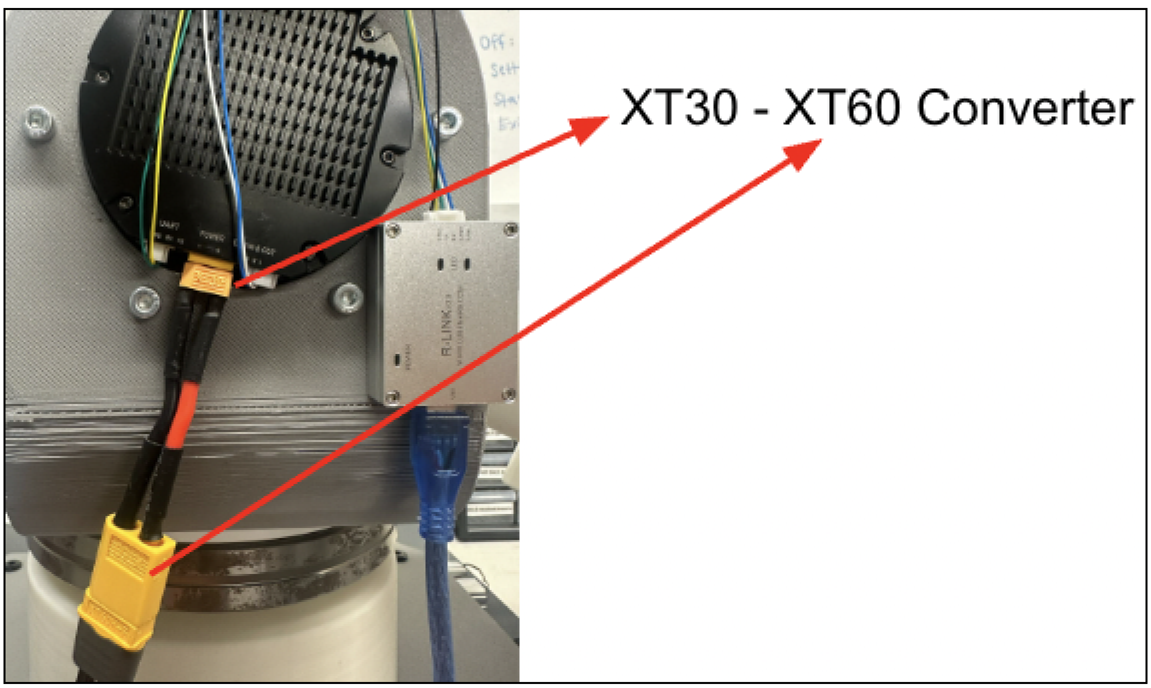

Figure 14. XT30-XT60 Converter

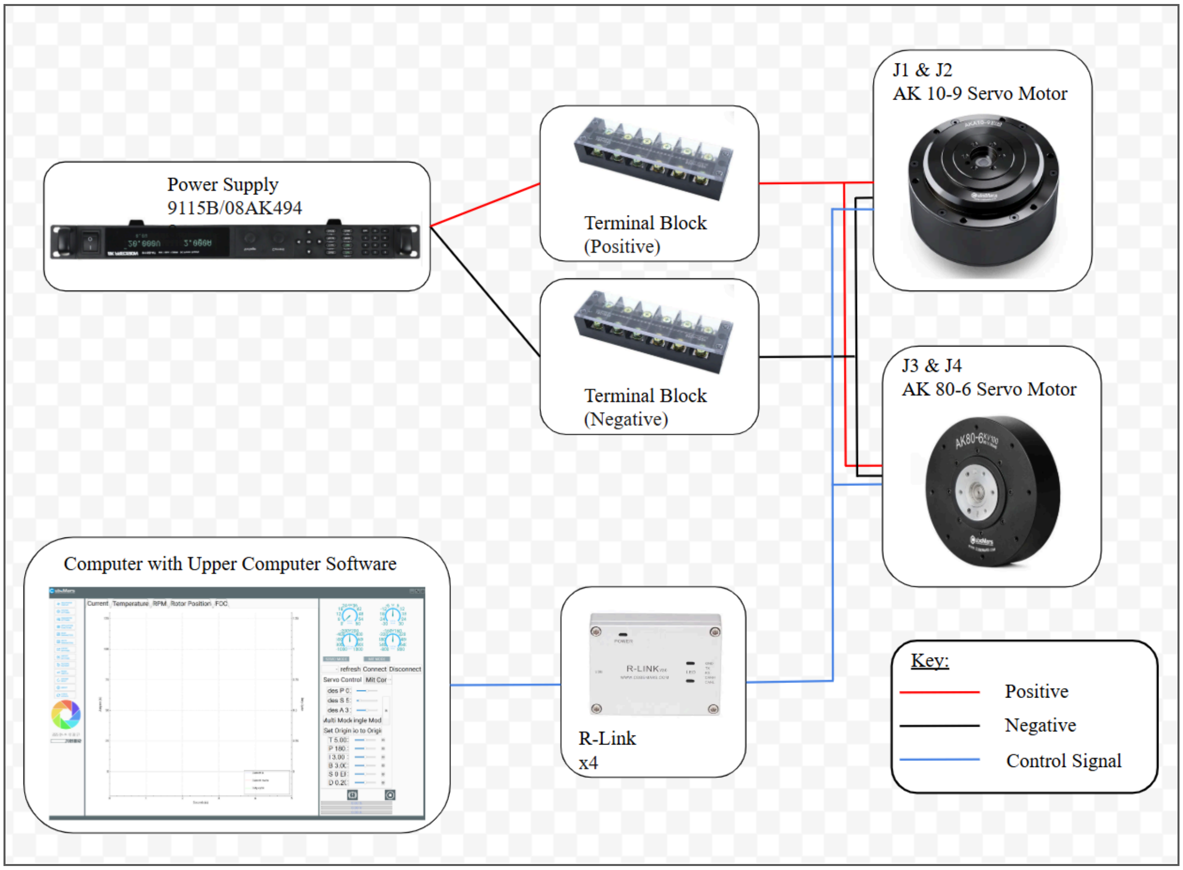

Figure 15. Overall Electrical Schematic

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. Embodiment Design Checklist, Risk Analysis, and Standards

3.1.1. 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, from uncertainty to certainty, and from 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 carefully considering the features mentioned above, the team came together and assessed the project to ensure that it was completed 100% with the design status 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 updated the resolution date to its actual completion date to keep a record of each milestone. A complete assessment of these key features can be found in **Appendix F.**

3.1.2. Risk Analysis FMECA

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 occurs, 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 the 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 G,** with the highest-rated failure mode for Fatigue from Repeated Motion on Crucial PLA supports receiving a RPN score of 144**.** In planning for this risk, the failure mode occurred during testing, where a crucial PLA component experienced enough fatigue to cause failure. The recovery plan included printing an entirely new piece with a stronger material and not being able to operate the machine until assembled back together..

3.1.3. Risk Analysis FTA

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 16.** 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. During the event, in which the PLA part failed, the team decided to print the part with a stronger and more durable material, which provided a more reliable component.

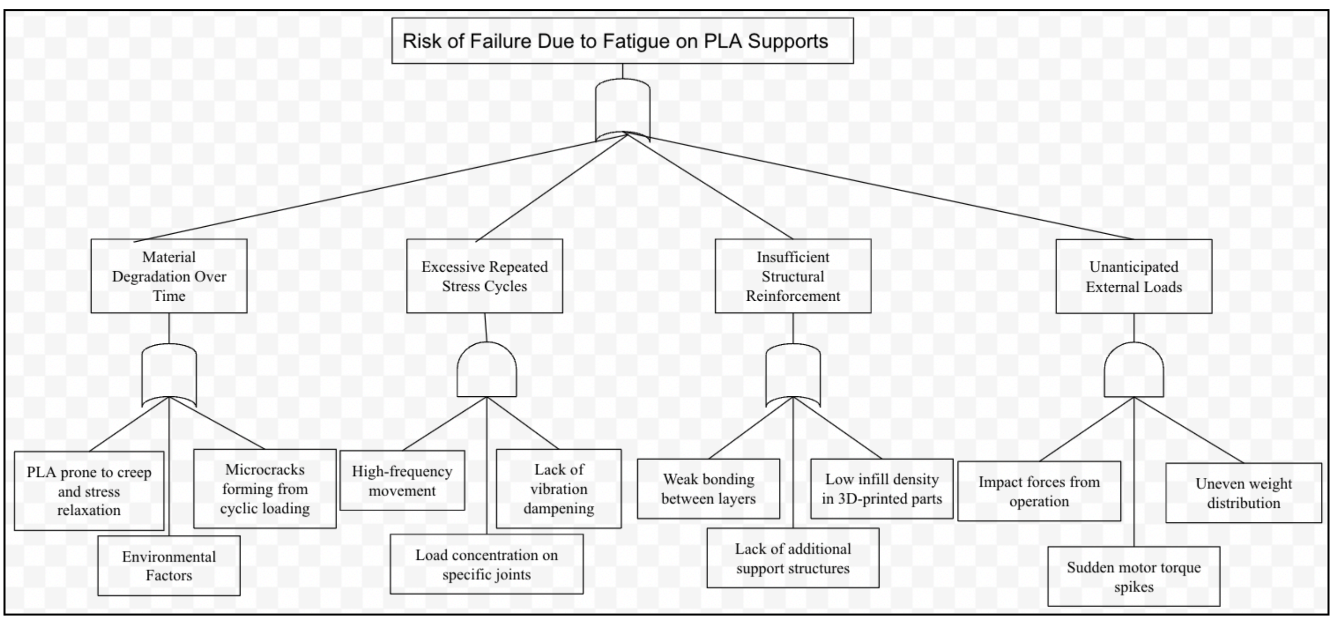

Figure 16: FTA Analysis for "Risk of Failure Due to Fatigue on PLA Supports"

3.1.4. Standards and Codes

There are a variety of standards and codes that are relevant to the robotic arm capstone. Some of these standards are out of scope for our capstone project. However, if the DOE or LANL were to implement this robotic arm in Hanford one day, these standards would apply. They can be found in Appendix H. Table H-1 includes Federal and State regulations that would apply to the robotic arm.

3.2. DFMA

The design of the robotic arm prioritized ease of prototyping and eventual scalability. With over 40 custom 3D-printed components across five subassemblies, the team used several DFMA strategies to reduce assembly complexity and improve part reliability.

3.2.1. Fastener Strategy and Evolution

The team standardized the use of M2.5-M6 socket head cap screws across joints, allowing for bulk ordering and simplified tool use during assembly. The variety in fasteners results from the various dimensions of the motors and bearings we selected. Long Allen wrenches were also utilized to help with assembly. While J1 originally did not feature counterbored holes, it became evident that protruding fasteners created clearance issues. In response, all subsequent joints incorporated counterbored holes to allow flush fits and tighter subassembly integration. For earlier joints, heat-set inserts were used extensively to thread into 3D-printed PLA. For the Bicep and Forearm, an open nut-and-bolt method was adopted instead. This reduced print failures due to melted insert installation and decreased the time spent soldering heat-set inserts. However, in the future, we would recommend designing the bicep and forearm to allow for heat-set inserts rather than the open concept. This concept works perfectly fine, but the tight angles to fasten can make it tedious to assemble.

3.2.2. Bearing Interface Modifications

For all joints using cross roller bearings (J1 and J4), friction between the rotating inner ring and PLA posed a risk of heat-induced deformation. To mitigate this, a precisely sized divot was integrated into the mushroom cap design to isolate the bearing inner race and minimize unwanted PLA contact and friction. This divot was added after J1's initial print showed early signs of thermal rubbing and was implemented proactively in J4.

3.2.3. Simplified Bearing Mounting and J5 Cylinder Cap

In J2, J3, and J5, the team relied on close tolerance fits (~1 mm) to set the ball bearing securely in printed holders. Tolerances tighter than 1 mm led to failed fits; >1 mm created looseness, so this dimension was standardized in later joints. The J5 bearing was too small to reliably support the required fastener hole pattern of the J5 Cylinder and J5 Motor on its own. A cylinder cap was introduced to distribute loading more evenly, match the hole pattern of the J5 motor, allow secure assembly, and allow us to use a properly sized ball bearing to match the size of the J5 motor.

3.2.4. Design Repeatability

To improve efficiency during prototyping and ensure consistency for future iterations, the team prioritized repeatability in the design of the robotic arm's joints. J1 and J4 were intentionally designed with mirrored features, as both joints utilize cross roller bearings to enable high-torque rotational motion. This allowed the team to reuse design elements such as the mushroom caps, motor holders, and bearing holders with minor dimensional adjustments, streamlining both modeling and manufacturing. Similarly, J2, J3, and J5 share a cylindrical design architecture focused on translational or pivot-like motion supported by ball bearings. Standardized geometries, such as bearing holders and motor mounting interfaces, enabled the reuse of fastener strategies and tooling across these joints. By maintaining consistent design principles within joint groups, the team reduced part variability, accelerated assembly, and simplified tolerance adjustments throughout the development process.

3.3. Design Validation

3.3.1. Motor Testing and Validation

To validate the robotic arm's performance, the team divided motor testing into two main phases: (1) individual motor testing outside the manipulator assembly and (2) integrated motor testing within the assembled robotic arm. Each motor underwent speed and position control tests to ensure it could accurately reach the required angles and move at the desired speed. The target actuation frequency was 1 Hz, equivalent to 6.28 rad/s, which was verified before testing due to a discrepancy between the units used in the upper computer. Before testing, the team identified that the upper computer accepted inputs in rad/s, not Hz. Therefore, all velocity-related inputs were converted appropriately. The team also explored tuning Kp (proportional) and Kd (derivative) control gains to optimize performance across three control modes: position, speed, and torque.

- **Position Control**: Kp = 3, Kd = 1
  → Provided responsive yet stable convergence to target angles.
- **Speed Control**: Kp = 0, Kd = 0.5
  → Prioritized damping over stiffness to minimize overshoot.
- **Torque Control**: Kp = 0, Kd = 0
  → Direct current control without feedback, used for passive holding.

These control gains were consistent across motors **J1–J4**.

3.3.2. Individual Motor Testing

To verify functionality and accuracy, each motor was tested independently on a custom stand. Motors were evaluated at angular positions of 0°, 90°, and 180°, and rotational speeds up to 6.26 rad/s. All motors responded reliably to commands issued through the upper computer interface. Representative data and setup images for J1 and J2 are provided in **Figures 17** and J3 and J4 are provided in **Figure 18.**

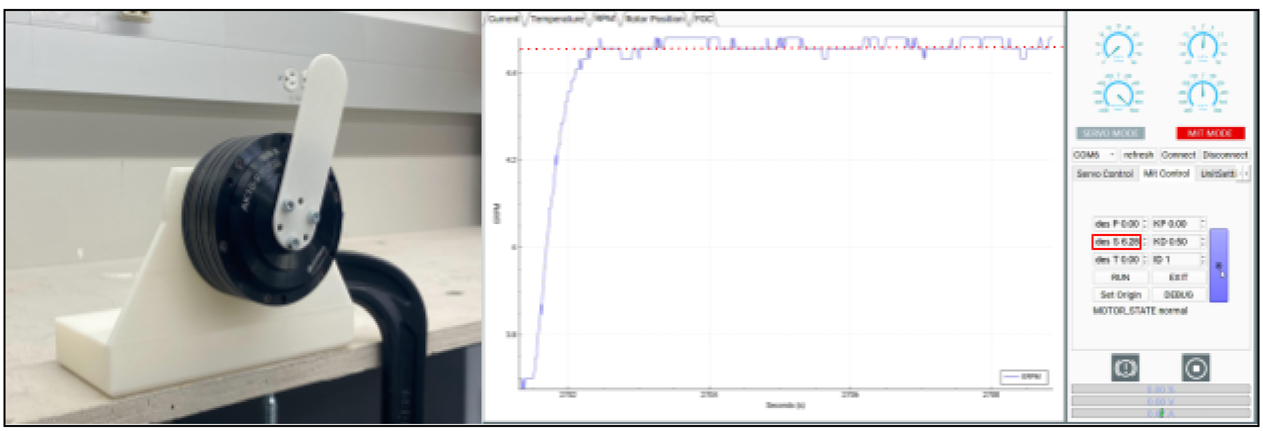

Figure 17: Individual Motor Testing - J1 and J2 Speed Data

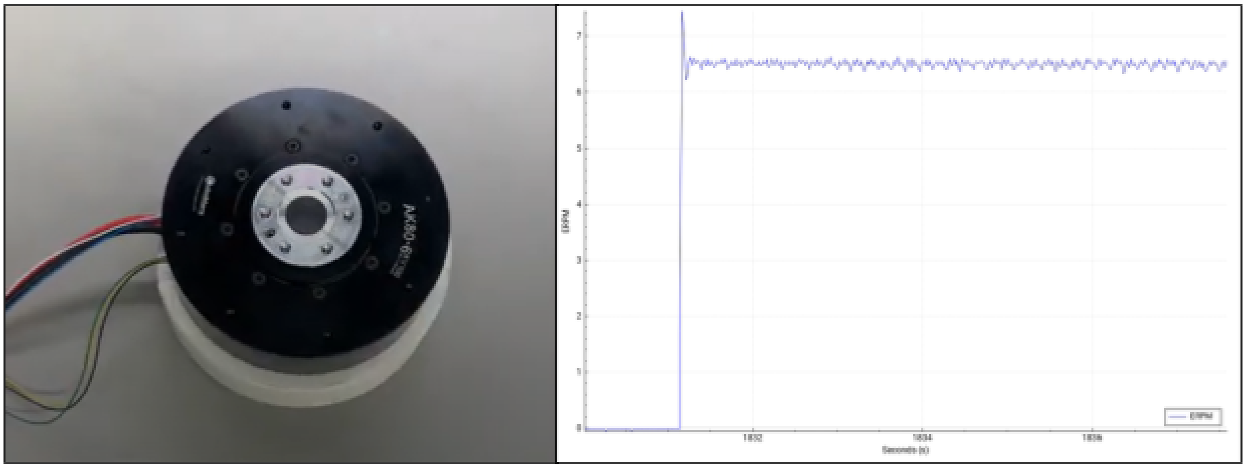

Figure 18: Individual Motor Testing - J3 and J4 Speed Data

3.3.3. Integrated System Testing

Following individual verification, motors were sequentially integrated into the robotic manipulator, starting from J1 through J4. The same position (0°, 90°, and 180°) and speed control tests (6.28 rad/s) were repeated post-integration and can be seen within **Figures 19 - 24**. During this phase, minor deviations from expected behavior were observed. Notably, each motor exhibited a consistent ~20° offset in the position control environment when fully assembled into the manipulator.

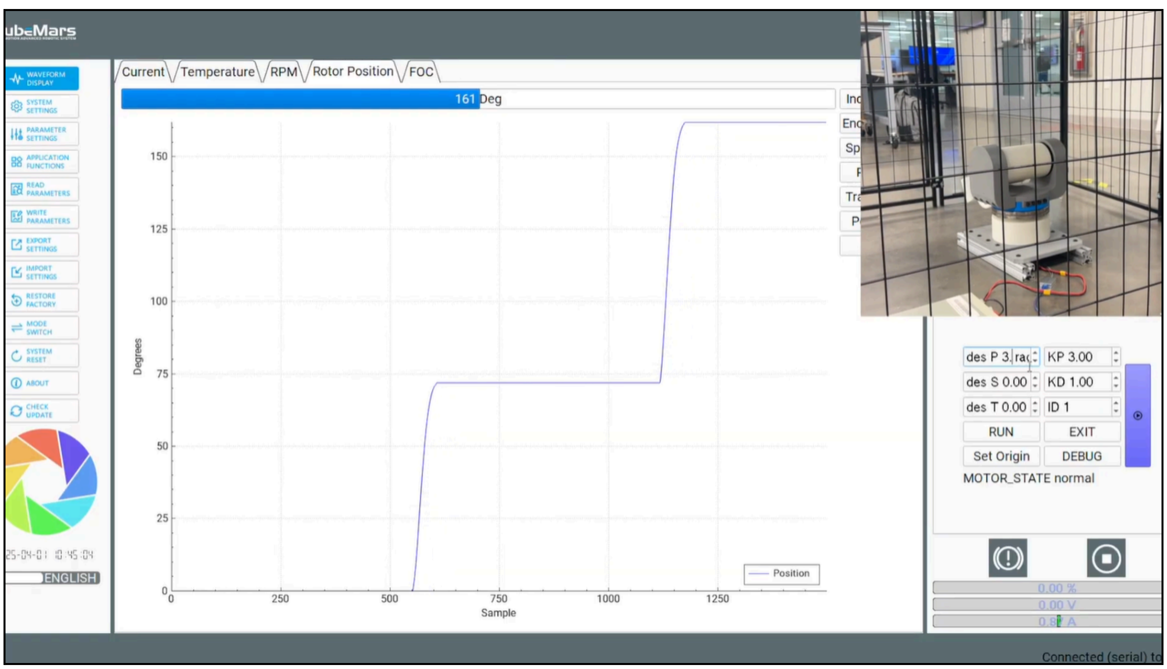

Figure 19: Integrated Motor Testing - J1 Position & Speed Verification

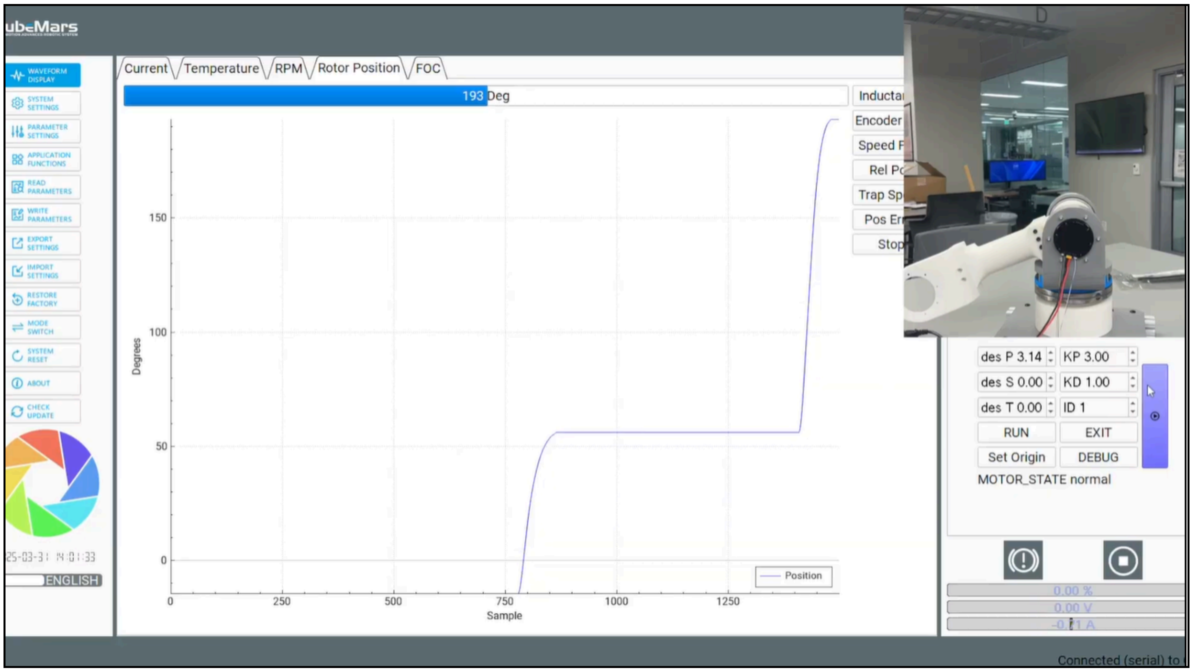

Figure 20: Integrated Motor Testing - J2 Position & Speed Verification

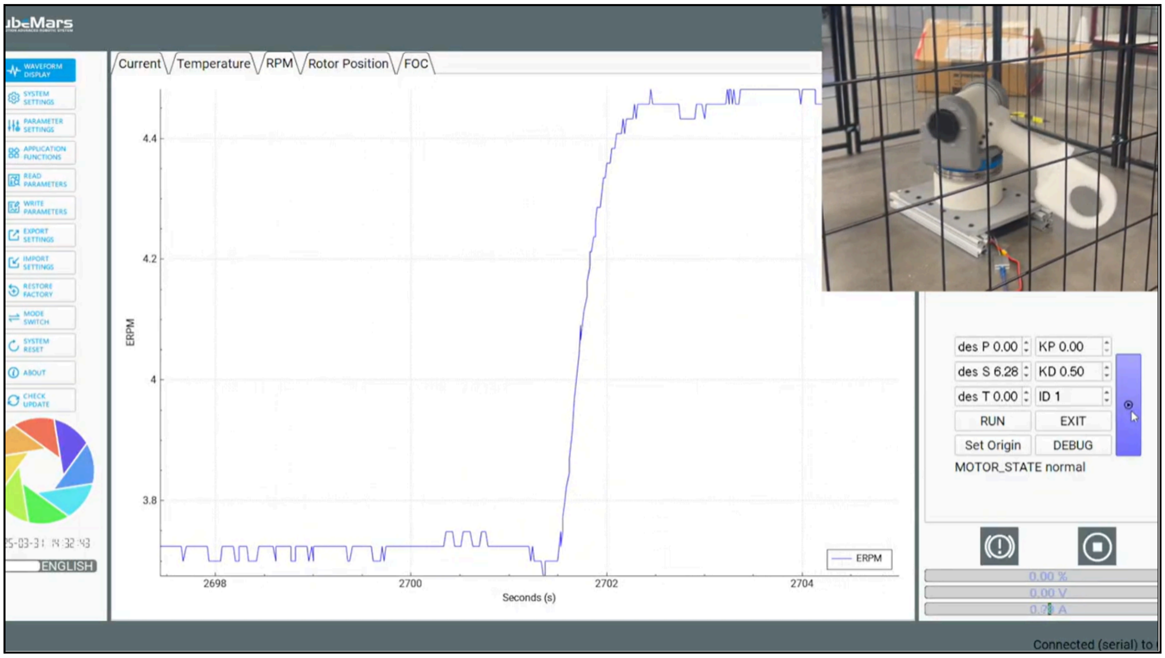

Figure 21: Integrated Motor Testing - J1 and J2 Speed Verification

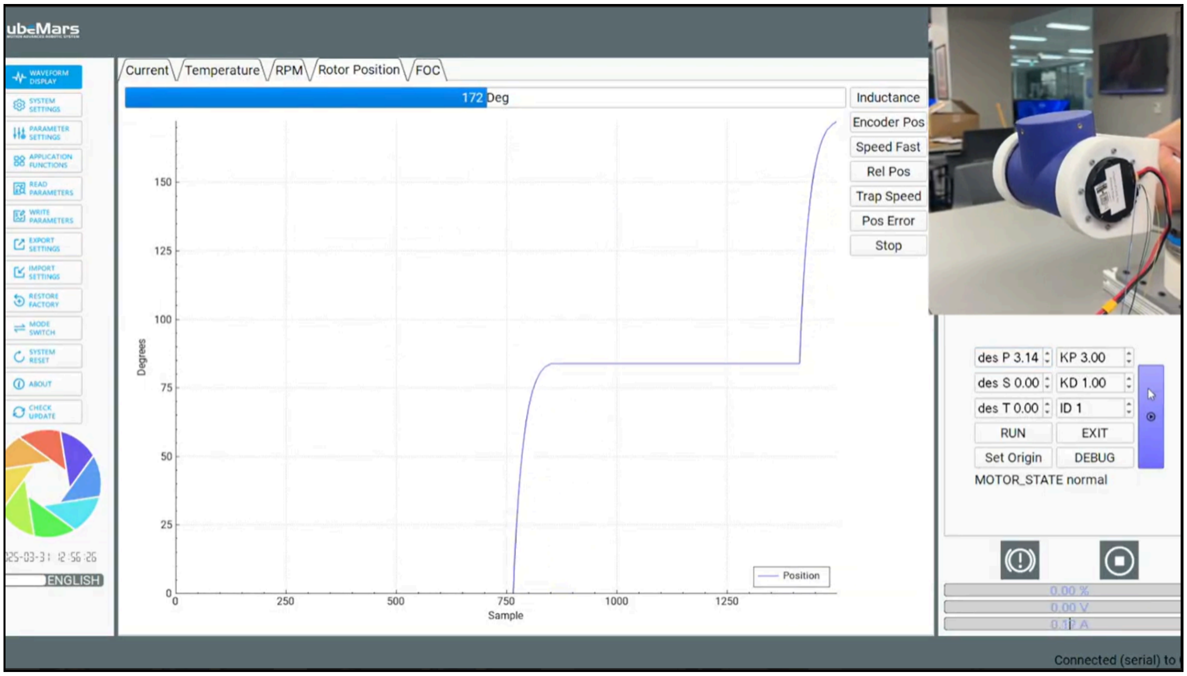

Figure 22: Integrated Motor Testing - J3 Position Verification

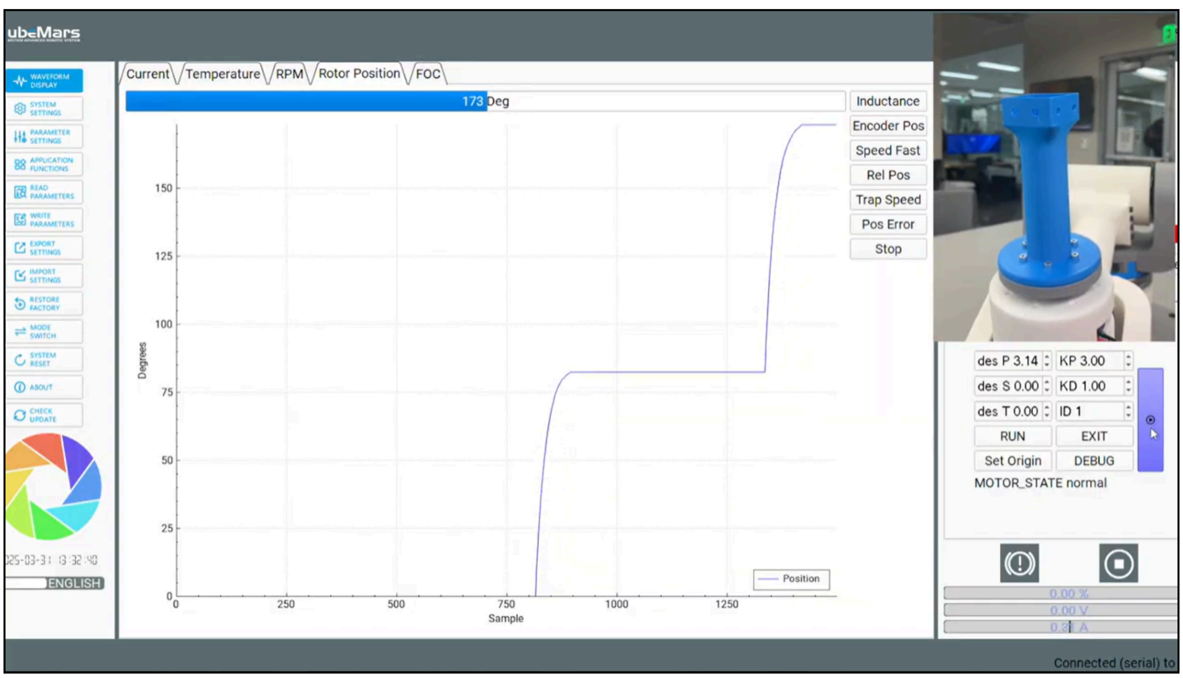

Figure 23: Integrated Motor Testing - J4 Position Verification

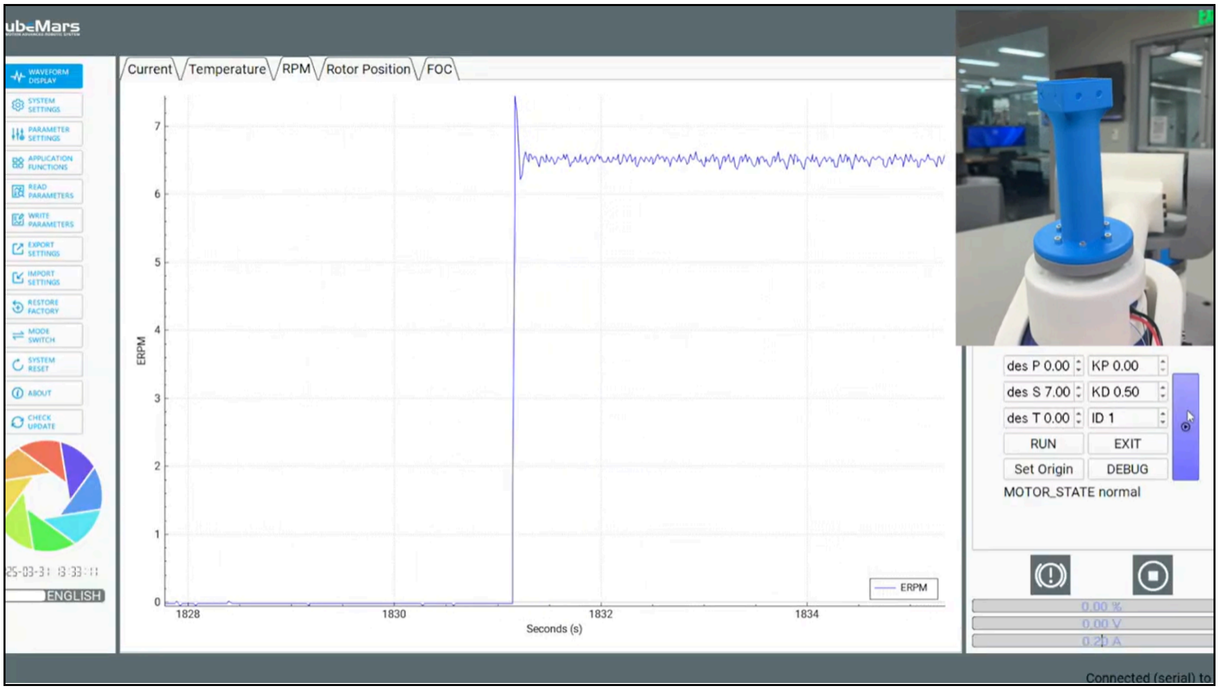

Figure 24: Integrated Motor Testing - J3 and J4 Speed Verification

This recurring error suggested either a software-side misalignment in the upper computer or a need to individually tune the Kp and Kd values for each joint. Additionally, during speed control testing, a notable discrepancy between commanded and actual motor speeds was observed. This was likely due to the added load from the manipulator's structure. To compensate, the input speed was gradually increased until the output response matched the target frequency of 1 Hz, and can be seen in **Figure 25**.

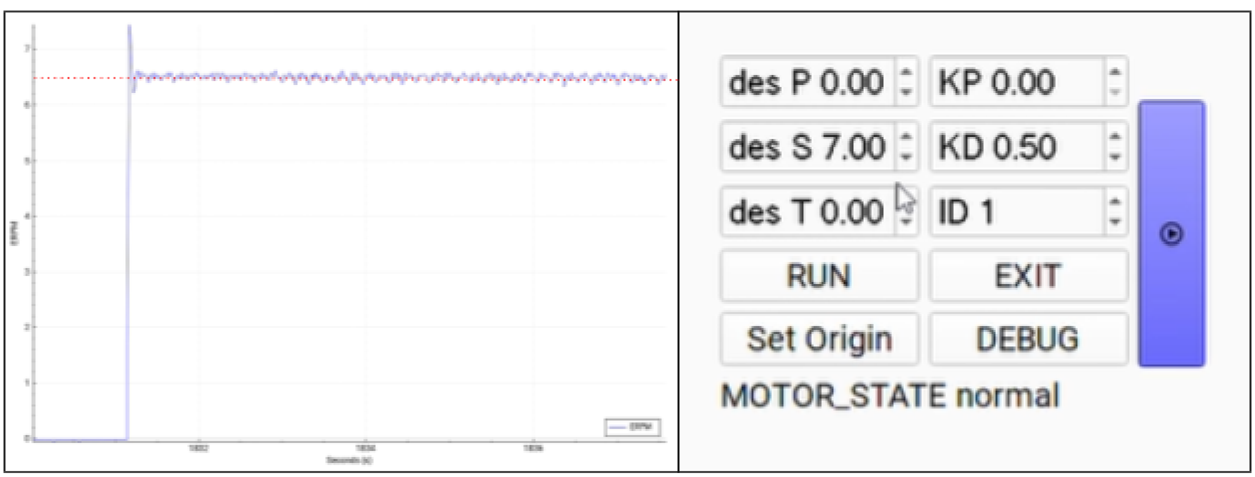

Figure 25: Compensation for Speed Verification

To accurately validate the torque requirement, particular attention was given to J2 and J3, as these joints experience the highest torque loads when the arm is fully extended. Validating motor performance under this configuration was critical to ensuring the robotic system could reliably support both static and dynamic loads during real-world operation.

3.3.4. Full Extension Load Testing

Using initial calculations from the previous semester, the team had estimated maximum torques during full-extension loading. This semester, real-world testing was conducted to compare these predictions with actual performance.

Table 4: J2 Full Extension Payload Calculations

Payload Analysis - J2 Max Length			
Type	**Weight (kg)**	**Length (mm) from J2**	**Overall Torque on J2 (Nm)**
A - aluminium extrusion	0.9	239	21.3286077
B - PLA	0.55	501.5	**Max Torque (Nm)**
C- PLA	0.738	684	42
J3 - AK80-6 KV100	0.485	478	**Mass Density (g/m^3)**
J4 - GL40 KV210	0.485	525	774
J5 - GL40 KV210	0.107	807	
B3	0.63	478	
B4	0.386	561	
B5	0.109	807	

Table 5: J3 Full Extension Payload Calculations

Payload Analysis - J3 Max Length			
Type	**Weight (kg)**	**Length (mm) from J3**	**Overall Torque on J3 (Nm)**
B - PLA	0.55	188	3.74079825
C- PLA	0.738	206	**Max Torque (Nm)**
J4 - GL40 KV210	0.485	47	12
J5 - GL40 KV210	0.107	329	**Mass Density (g/m^3)**
B4	0.386	83	
B5	0.109	329	

Table 6: J2 & J3 Full Extension Actual Payload

Motor	**Actual Torque Value**
J2	20 Nm
J3	2 Nm

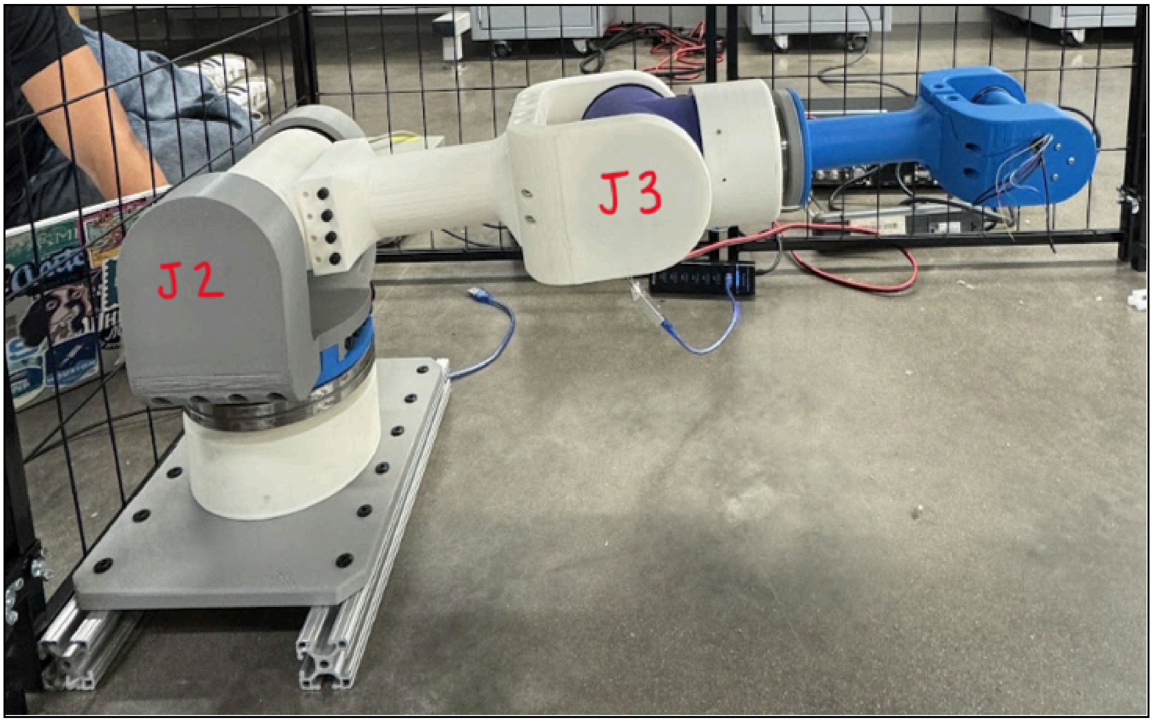

Figure 26: Robotic Manipulator at Full Extension with J2 & J3 Torque Inputs

Despite theoretical torque demands slightly exceeding the actual torque demands, practical testing confirmed that the manipulator could sustain full extension without collapse, validating the design choices made during motor selection.

Overall, the robotic arm was systematically validated under three control conditions—position, speed, and torque—and successfully met the performance criteria required for reliable 5-DOF operation. The system demonstrated accurate joint positioning, achieved the target actuation frequency of 1 Hz, and maintained structural stability while fully extended.

3.4. Comparison of Design

It is important to highlight the original design requirements set out in collaboration with Dr. Mascerenas and the team in the design requirements phase of the project, which can be seen in **Table 7**. These requirements were established by analyzing the sponsor's needs and the objectives outlined in the problem statement.

Table 7: Robotic Manipulator LANL - Design Requirements

Requirement #	Metric	Importance Score (1 to 5, 5 = most important)	Required Values	Units
1	Weight of the Arm	3	<14	kg
2	Minimum Torque Output	3	2-10	Nm
4	Reach of Robotic Arm	3	>0.67	m
5	System Mass Distribution	2	0.209	kg/cm
7	Frequency of Motion	5	1	Hz

Through comprehensive team validation, several critical performance metrics of the robotic arm were successfully evaluated against the defined requirements. First, the weight of the arm was measured at 26.2 lb (11.88 kg), well below the maximum allowable weight of 14 kg. To hold itself up, each motor needed to be able to sustain a minimum torque output. This value varies depending on the joint of the robot and the position of the arm. During torque testing, the team was able to perform isolated testing of the two AK 10-9 Motors and the two AK 80-6 Motors. To determine the torque required for the robotic arm to support itself, the robot was positioned as shown in the figure below:

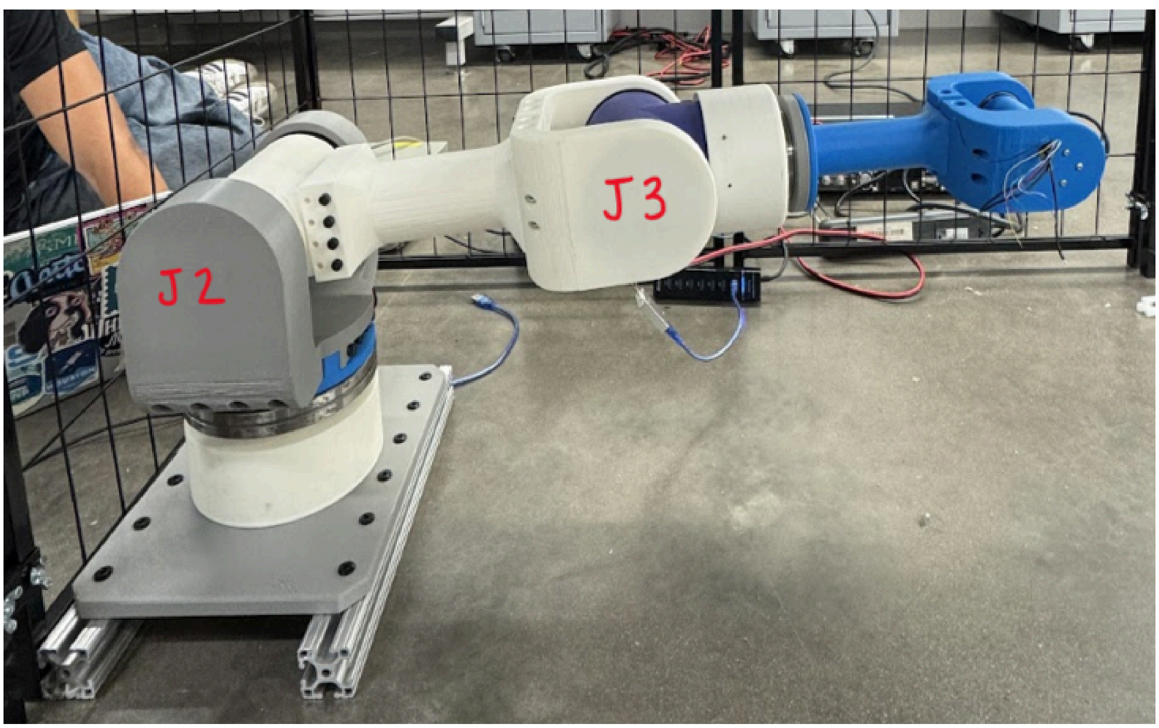

Figure 27. Robotic Manipulator at Full Extension with J2 & J3 Torque Inputs

To maintain this position, Joint 2 (AK 10-9 motor) exerted a torque of 20 Nm, while Joint 3 (AK 80-6 motor) provided 2 Nm. The remaining joints were unpowered, so the entire load of the arm was supported solely by the J2 and J3 motors. The AK 10-9 motor is utilized in the J1 and J2 joints, and the AK 80-6 motor is utilized in the J3 and J4 joints. Although not every joint was individually tested for this torque metric, the motors performed reliably in the joints that experienced the highest torque demands. This confirmed that the motors are capable of providing sufficient torque across the entire arm under normal operating conditions.

This lightweight design contributes to the overall efficiency and maneuverability of the system. Furthermore, the robotic arm demonstrated a maximum reach of 0.9 meters at full extension, exceeding the requirement of 0.67 meters and effectively mimicking the reach of a human arm. The system's mass distribution was calculated to be 0.132 kg/cm (11.88 kg distributed over 90 cm), which is below the established system mass distribution threshold. This was calculated by dividing the total measured weight of the robot (11.88 kg) by the total length of the arm (90 cm).

The most critical requirement identified was the ability of the arm to operate at a continuous movement of a frequency of 1 Hz. This is the time it takes the motor to complete 1 cycle of movement. The sponsor placed the highest priority on achieving rapid arm movement. Individual motor tests at each joint confirmed that all selected motors met the specified frequency (Hz) requirements with accurate execution. Each motor was tested for completing a cycle of rotation at 6.28 rad/s.

Validation and testing proved that the robotic arm successfully met and exceeded several key performance requirements. Most notably, the arm demonstrated the ability to move rapidly and sustain continuous motion at a frequency of 1 Hz, addressing the sponsor’s highest priority. These results collectively validate the arm’s capability to perform with speed, precision, and reliability.

3.5. Cost Accounting and Cost Model

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 a team, we spent approximately $4,350, 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.

With the support from campus resources, the team created two cost models. **Figure 28** provides a summary of the current Bill of Materials, summarizing the components the team purchased through the Texas A&M Mechanical Engineering Department. **Figure 29** combines both the purchased and borrowed components, creating an entire cost model for future groups to replicate the project. The final product is estimated to cost around $8,500.

ORDER #	QTY	ITEM #	DESCRIPTION	VENDOR	LINK	UNIT COST	COST	
1	2	AK10-9 V2.0 KV100	Brushless DC Motor with driver board	Amazon	https://www.ama	$798.90	$1,597.80	
2	2	AK80-6 KV100	Brushless DC Motor with driver board	Robotshop	https://www.robo	$712.90		**Being ordered by sponsor
3	1	GL40 KV70	Gimbal Motor with encoder	Amazon	https://www.ama	$97.99	$97.99	
4	1	Aluminum Beam	1 ft Multipurpose 6061 Aluminum Rectangular Tube	McMaster-Carr	cmaster.com/6546	$40.47		**Refunded
5	1	Bearing - Crossed Roller	J1 Bearing: 80mm shaft High-Load Face-Mount Crossed-Roller Bearing	McMaster-Carr	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	/w.mcmaster.com/	$36.12	$36.12	
8	1	Ball Bearing	J4: 35mm High-Load Face-Mount Crossed-Roller Bearing	McMaster-Carr	vw.mcmaster.com/	$217.66		**Refunded!
9	1	Ball Bearing	J5 Bearing: 20mm shaft Ball Bearing	McMaster-Carr	/w.mcmaster.com/	$13.12	$13.12	
10	3	94180A371	M6 x 1 mm Thread Size, 7.6 mm Installed Length	McMaster-Carr	w.mcmaster.com/9	$13.80	$41.40	
11	1	90128A332	M4 x 0.7 mm Thread, 15 mm Long	McMaster-Carr	w.mcmaster.com/9	$9.71	$9.71	
12	1	91290A049	Black Oxide, M2 x 0.4 mm Thread, 20 mm Long	McMaster-Carr	w.mcmaster.com/9	$15.21	$15.21	
13	1	91290A323	Black-Oxide, M6 x 1 mm Thread, 18 mm Long	McMaster-Carr	w.mcmaster.com/9	$19.58	$19.58	
14	1	91290A194	Black-Oxide, M5 x 0.8 mm Thread, 30 mm Long, Fully Threaded	McMaster-Carr	w.mcmaster.com/9	$5.74	$5.74	
15	1	91274A117	M4 x 0.7 mm Thread, 10 mm Long	McMaster-Carr	w.mcmaster.com/9	$5.28	$5.28	
16	2	94180A361	M5 x 0.8 mm Thread Size, 6.7 mm Installed Length	McMaster-Carr	w.mcmaster.com/9	$17.86	$35.72	
17	1	91290A248	Black-Oxide, M5 x 0.8 mm Thread, 22 mm Long	McMaster-Carr	w.mcmaster.com/9	$12.08	$12.08	
18	1	91290A316	Black-Oxide, M6 x 1 mm Thread, 10 mm Long	McMaster-Carr	w.mcmaster.com/9	$15.13	$15.13	
19	1	90128A212	M4 x 0.7 mm Thread, 10 mm Long	McMaster-Carr	w.mcmaster.com/9	$9.49	$9.49	
20	1	90128A208	M4 x 0.7 mm Thread, 6 mm Long	McMaster-Carr	w.mcmaster.com/9	$10.42	$10.42	
21	1	91290A222	Black-Oxide, M5 x 0.8 mm Thread, 8 mm Long	McMaster-Carr	w.mcmaster.com/9	$12.75	$12.75	
22	1	Heat Set Insert Tool Tips	Tips for Threaded inserts M2 M2.5 M3 M4 M5 M6	Amazon	x2-c7usoBtj7COnZ	$9.99		**Refunded
23	1	CRAFTSMAN Storage Organizer	30 Small Drawer Modular Storage System	Amazon	5OyBtYePXZkiW-L6	$20.98	$20.98	
24	1	Dog Kennel Outdoor	4'L x 4'W x 4.5'H	Amazon	&pf_rd_p=cd15227	$159.99	$159.99	
25	1	T-nut Slots	20PCS 4040 Series M6 T-Nut	Amazon	trusion-Profile-8m	$15.49	$15.49	
26	1	Black Flat Head Allen Head Joint Conecting Bolts	12-Pack M6 x 22mm	Amazon	AIJAQjc1XbLI3XC16	$7.99	$7.99	
27	4	CubeMars R-link V2.0	Debugging tool for AK Motors	RobotShop	-link-v20-debuggin	$51.90	$207.60	
28	1	T-Key allen wrench set	8pc set Metric MM sizes 2-10	Amazon	IUCQ?source=ps-s	$14.46	$14.46	
29	1	94180A351	M4 x 0.7 mm Thread Size, 4.7 mm Installed Length	McMaster-Carr	w.mcmaster.com/9	21.82	21.82	
30	1	94180A331	M3 x 0.5 mm Thread Size, 3.8 mm Installed Length	McMaster-Carr	w.mcmaster.com/9	20.44	20.44	
31	1	92095A177	Passivated 18-8 Stainless Steel, M3 x 0.50 mm Thread, 5mm Long	McMaster-Carr	w.mcmaster.com/9	7.39	7.39	
32	1	IVETTO Brand	7-port USB port	Amazon	-20&linkCode=df0	$19.99	$19.99	
33	1	Hanglife Store	Heat-set Threaded Inserts M2.5	Amazon	uk-axKA2OlZFuYaU	$8.99	$8.99	
34	1	4471N14	Face-mount Crossed-Roller Bearing	McMaster-Carr	vw.mcmaster.com/	$586.42	$586.42	
35	1	XT30 to Orings	14AWG Silicon Cable XT30 to O Ring Terminal Cable	Amazon	gH_CYY5mPL5t-F	$6.39	$6.39	
36	2	Dual Row Screw Terminal Strip	Terminal Block 6 Position 600V 100A	Amazon	-Dual-Rows-Term	$12.09	$24.18	
37	5	XT60 to Orings	12 AWG 1.5 M	Amazon	dib_tag=se&key	$13.27	$66.35	
38	2	Converter	XT30F to XT60M	Amazon	_A2_3D-Q_iyVKI	$4.69	$9.38	
39	1	Battery Cable	6 AWG 5 feet	Amazon	p6TXN2NNAcO8I	$25.99	$25.99	
40	1	Cable Mesh	10 ft 1/2 inch	Amazon	xmb2k9-22lFzJzq	$7.63	$7.63	
41	4	Long USB Extension Cable	10 foot, Black	Amazon	21U?source=ps-s	$8.49	$33.96	
					Additional Customs Fee		514.41	
					Shipping (McMaster)		51.28	
						TOTAL	$4,329.63	

Figure 28: Purchased Bill of Materials

Univeristy/Sponsor Inventory						
Part	**Part Number**	**Vendor**	**Cost each**	**Qty**	**Total Cost**	**Notes**
Power Supply	9115B/08AK4948	Newark	$2,550.00	1	$2,550.00	80V, 60A
4040 T-slot Aluminum Extrusion	350 millimeter	FEDC	$9.75	2	$19.50	
3D Printed Parts	Printed using PLA	RPS	N/A	N/A		
M6 x 20mm	N/A	RPS	$9.99	1	$9.99	
Soldering Iron	Used to insert heatset inserts into PLA parts	RPS	$16.99	1	$16.99	
M3 x 4mm	N/A	RPS	$6.99	1	$6.99	
M4 x 8mm	N/A	RPS	$11.89	1	$11.89	
M6 Washers	N/A	RPS	$4.99	1	$4.99	
M6 Hex Nuts	N/A	RPS	$9.99	1	$9.99	
M2.5 x 6mm	N/A	RPS	$7.29	1	$7.29	
M2.5 x 5mm	N/A	RPS	$7.19	1	$7.19	
M4 washers	N/A	RPS	$4.99	1	$4.99	
M4 Hex Nuts	N/A	RPS	$9.99	1	$9.99	
				Customs Fee	$514.41	
				Shipping	$51.28	
				Total	$8,366.06	

Figure 29: University/Sponsor Inventory (**including Purchased Components)

4. Broader Impacts of Design

The design and development of the robotic arm was guided not only by technical performance metrics but also by broader considerations that influence its long-term impact, safety, sustainability, and ethical use. This section explores the intellectual property status of the system, evaluates liability considerations in both prototype and future deployment scenarios, and outlines lifecycle design choices made to enhance the arm's maintainability, longevity, and environmental responsibility. Additionally, ethical concerns related to safety, transparency, and responsible engineering practice are discussed in detail. As the system is intended for future use in a national laboratory setting, these broader impacts are especially critical to ensure it operates safely, remains maintainable, and aligns with regulatory and environmental standards.

4.1. Lifecycle Design

Maintenance and longevity were key considerations in the design of the robotic arm, particularly in anticipation of future iterations that may involve harsh environments. Currently, the design utilizes brushless DC motors, which require minimal maintenance. All the motors are CubeMars brushless DC motors, which are engineered for low maintenance due to a brushless DC design that minimizes wear-related servicing. Although the motors are designed for low maintenance, there are several procedures that can be conducted for routine maintenance of the motors. This includes: visual and electrical inspections, cleaning, environmental monitoring, and load management. To maximize the lifecycle of electrical components, the electrical components were wrapped in wire mesh to properly contain electrical components and ensure that they do not become unplugged. The team ensured the motors were kept at the proper operating temperature of –20 °C to 65 °C. The robot was constructed out of lightweight material to ensure the motors were not subjected to overload conditions in order for the robot to hold itself up.

The linkage joints of the arm are fabricated out of 3D printed PLA plastic. PLA was chosen due to its lightweight properties and high dimensional accuracy for printing, however, it has limitations in environmental resistance. PLA can begin to show warping after extended mechanical stress. This typically occurs within 1-2 years, depending on the usage or intensity. Because of this, the team recommends reprinting the arm from PETG, which is much more durable.

Among all components, the motors are likely to have the shortest operational lifespan, depending on usage intensity and environmental conditions. However, the robotic arm's modular design enables each joint to be disassembled independently, allowing for quick and efficient motor replacement without dismantling the entire system. In the event of structural failure, such as a broken linkage, the affected part can be easily reprinted using the design files available on the project's GitHub repository. These linkages are made from PLA, a biodegradable thermoplastic, which can be responsibly disposed of through industrial composting where facilities exist. Additionally, any failed electronic components should be handled through certified e-waste recycling programs to reduce environmental impact and promote responsible end-of-life management.

4.2. Intellectual Property (IP)

The robotic arm project does not currently contain or involve any intellectual property, in the context of patents, trademarks, copyrights, or trade secrets. Although the design is original, it does not include any novel and non-obvious aspects that would warrant Intellectual Property protection. The design of the robotic arm was inspired by the design of robotic arms in industry, and the construction relied on commercially available components and open-source software. Standard engineering practices commonly found in academic and industry settings were utilized. No novel algorithms, mechanical innovations, or unique control systems were developed that would meet the criteria for patentability or proprietary protection. Additionally, all design files, documentation, and code were created for educational purposes (National Laboratory) and intended for open sharing within the academic community, further limiting the potential for IP claims. To support this, the team has made the project publicly available through a GitHub repository, allowing others to follow its development, learn from the process, and potentially replicate the design.

4.3. Liability Considerations

Prototype

The main liability considerations for the project involve safety risks due to physical interaction and motion control of the robotic arm. Pinch points, unexpected movements, and mechanical failure are the main factors that could cause injury during testing or demonstration. To mitigate these risks, the team implemented a safety cage around the robot to provide a physical barrier of protection. This allowed the team to conduct testing without the concern of injury from unexpected movement or motor failure. The team also limited motor torque and speed during testing to reduce the risk of failure and unexpected movement. Since the project is intended for educational use in a National Laboratory, formal product liability concerns (such as consumer safety regulations or warranty obligations) do not currently apply.

Production

The goal of this design is to be utilized at a national laboratory to clean up hazardous waste by remote operation. Due to this, the robotic arm would need to be in compliance with federal regulations such as OSHA (Occupational Safety and Health Administration) and DOE (Department of Energy). Liability could arise if the system causes injury to personnel, damages sensitive equipment, or fails to perform as expected in a way that leads to operational disruption.

4.4. Ethical Considerations/Concerns

User safety was treated as the most important ethical priority throughout the project. The team implemented safety protocols such as limiting operational speed and torque during testing and utilizing a safety cage to reduce the risk of injury. This was implemented to keep each team member safe throughout the entire prototyping and testing process by creating a physical barrier between the robot and team members. Because this robotic arm is intended for manual use, it is critical that the robot operates predictably and does not endanger users or bystanders. Another key ethical concern was transparency and honesty in system performance reporting. The team prioritized presenting accurate and consistent updates to ensure that the sponsor and studio professors were accurately informed about the system's capabilities throughout the entire prototyping process. This was achieved through constant communication with the sponsor in the form of emails and consistent update meetings. The studio professor was kept informed through weekly update meetings held during each studio session.

5. Summary

5.1. Work Breakdown Structure (WBS)

A Work Breakdown Structure (WBS) is defined as a hierarchical decomposition of a project into smaller components; an assembly of tasks that correspond to a particular activity performed on a project. The arrows included in this structure direct the reader along the path of subsequent tasks taken to reach the overall larger deliverable. The WBS made for the team's robotic arm can be seen in **Figure 30**. Creating the Work Breakdown Structure (WBS) for the 5-DOF robotic arm was an essential step in transitioning from the design phase to implementation. The WBS was developed by identifying all major tasks required to bring the system from a digital model to a fully functioning prototype. This included organizing the work into logical categories such as 3D printing, motor and electronics setup, mechanical assembly, communication integration, testing, and final deployment. Each category was then broken down into smaller, manageable work packages to clearly define the scope, sequence, and dependencies of tasks. By outlining this hierarchy, the WBS provided a clear roadmap for manufacturing, assembling, and validating the robotic arm, ensuring that nothing critical was overlooked and allowing team members to focus on specific areas of responsibility during the build process.

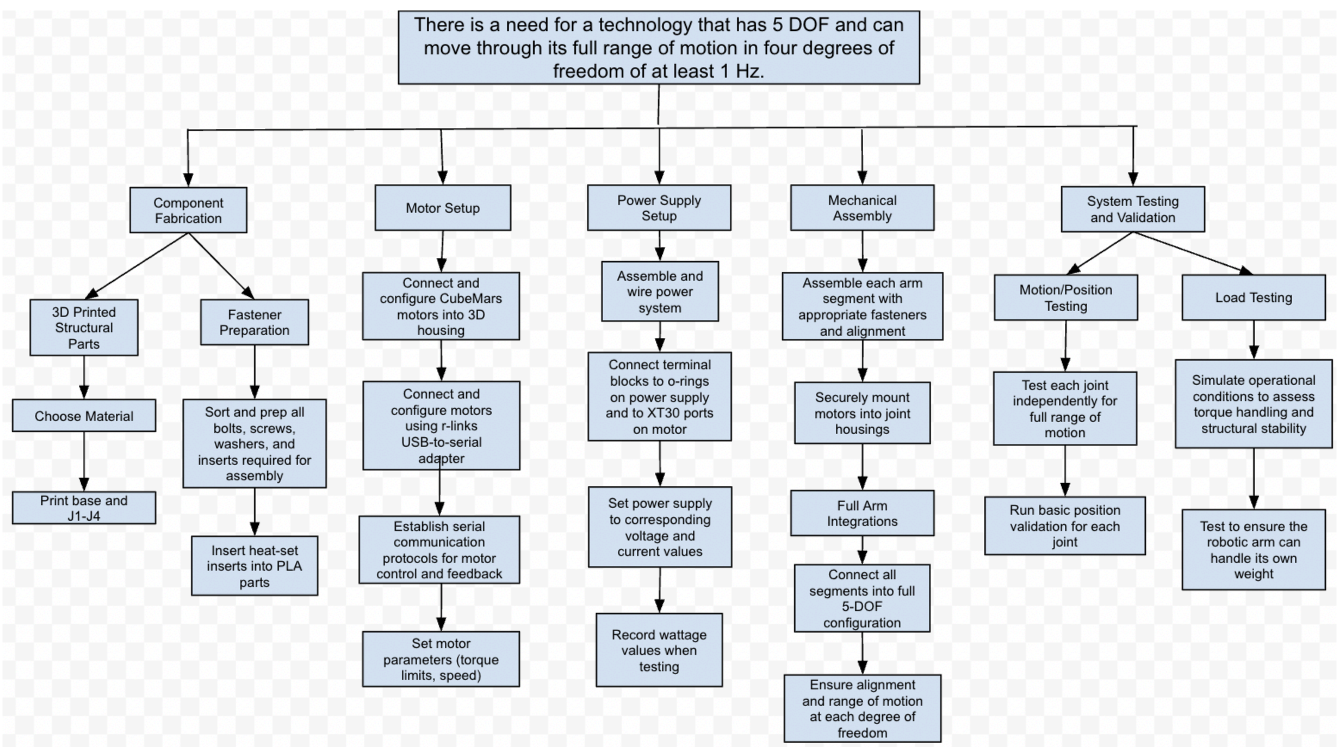

Figure 30. Work Breakdown Structure of Design Implementation

5.2. Final Gantt chart and Project Plan

A critical tool used within project management to relay scheduling and individual tasks is a Gantt chart. A Gantt chart is a graphical representation that includes task sequencing, task dependencies, milestones, resource usage, critical path, and personal responsibility. This chart combines the order of tasks identified on the task dependency diagram with the personal requirements outlined in the work breakdown structure. Each task is presented on the far left side of the chart and is followed by a highlighted section that corresponds to the dates associated with that task. The dates for that task can be seen in the top row of the chart. The entire schedule for the Spring 2025 semester is shown in **Figure 31.** The color components of the chart represent the progress of each task, identified as either "planned", "in progress", or "completed". The availability for the team is also included on the chart, including dates of holidays and personal unavailability due to other commitments, specifically Spring Break.

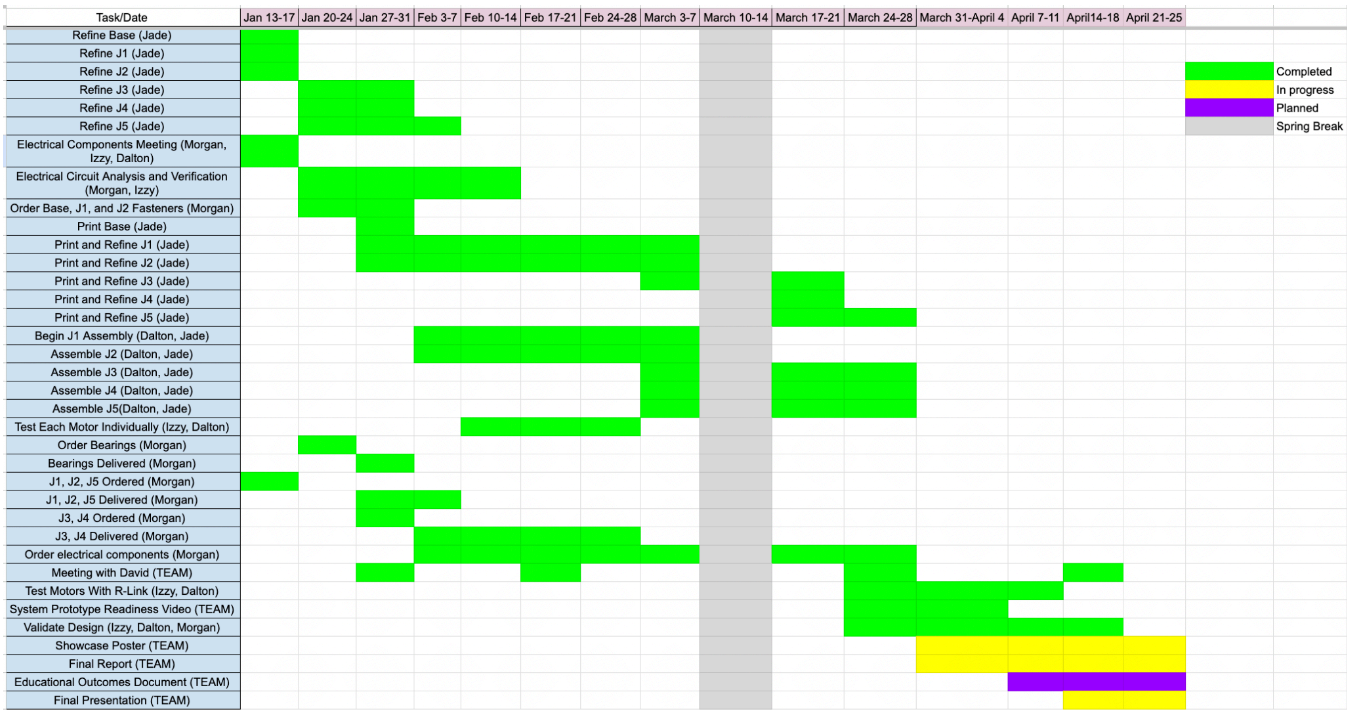

Figure 31. Spring 2025 Gantt Chart

5.3. Technology Development

5.3.1. Controls Technology Development

One significant challenge the team encountered was the difficulty in controlling the J5 motor (GL40 Gimbal Motor), which is unable to connect to the R-link serial-to-USB communication device. As a result, the team was unable to control the fifth joint of the robotic arm. To address this issue, the team reached out to the motor manufacturer, CubedMars, for guidance on compatible control solutions.

CubedMars recommended that the team contact Elmo Motion Control, a company specializing in motion control systems. After discussing the intended use of the GL40 Gimbal Motor as the wrist joint of the robotic arm, Elmo Motion Control suggested two products that would work seamlessly with the motor:

- G-DCWHI2.5/100SESQ – a high-performance servo driver
- CBL-GDCWHIKIT02 – a wiring kit specifically designed for use with the driver

By implementing these products, future teams will be able to connect the servo driver to a power source and use it to effectively control the gimbal motor, ensuring proper functionality of the fifth joint in the robotic arm.

Implementing the design of the robotic arm, particularly the control of the J5 motor (GL40 Gimbal Motor), requires a strong understanding of motion control systems, including knowledge of motors, feedback loops, and communication protocols. To successfully integrate the motor into the system, one must be proficient in configuring and calibrating servo drivers, such as the G-DCWHI2.5/100SESQ, and understand the role of each component in the control chain. Familiarity with serial communication protocols, such as CAN bus, is essential for linking the motor to a control system, and an understanding of electrical wiring and circuit design is necessary to ensure proper connections between the driver, motor, and power sources. Additionally, a grasp of real-time control systems and software integration is critical for programming and fine-tuning the motor's response, ensuring smooth, precise movement of the robotic arm.

To further this design and control multiple motors, the use of a CAN bus and Arduino should be explored. Controlling multiple motors with a CAN bus and an Arduino involves using the CAN protocol to enable communication between the Arduino and each motor, with each motor assigned a unique CAN ID. The Arduino, equipped with a CAN transceiver like the MCP2515 module, sends commands to motor drivers over the bus, which then adjust the motor's behavior based on parameters such as speed or position. The Arduino uses libraries like "MCP_CAN_lib" to structure and send messages, ensuring synchronization across motors. Managing multiple motors requires careful message prioritization and timing to avoid bus congestion, with techniques like message filtering and acknowledgments to maintain efficiency. This setup enables smooth, real-time control of complex robotic systems with several motors, offering scalability and reliability for advanced applications.

5.3.2. Electrical Technology development

Another significant challenge faced during the design was developing a wiring solution that would accommodate the robot's ability to perform 360-degree rotations without entangling or restricting its movement. To achieve continuous, free rotation, a split-ring design is necessary, which ensures the wiring can remain connected without becoming twisted or tangled as the robot spins. This design is especially crucial because the robot utilizes brushless DC motors, which require a stable, uninterrupted power supply for optimal performance. The split-ring mechanism allows electrical connections to rotate with the motors while maintaining signal integrity, enabling smooth motion across all axes without risk of wire interference. This implementation ensures that the robotic arm can function with full range of motion, both safely and efficiently, while keeping the system's electrical components securely connected. A split ring for this application would need to be custom-designed to ensure it fits the specifications of the robotic arm.

5.4. Limitations

5.4.1. Constrained Joint Coordination and Computational Bottleneck

The current robotic arm exhibits an inability to accomplish simultaneous multi-joint motion, except in instances of multiple connections to the upper computer. This limitation introduces a computational bottleneck that restricts the arm's ability to accomplish complicated, coordinated functions efficiently. The need for distinct control paths to distinct joints avoids the utilization of smooth motions that are crucial to quick manipulations in a 3D space.

5.4.2. Lack of Autonomous Gravity Compensation

A prominent limitation is the arm's inability to automatically compensate for gravity within its workspace. Pre-programmed or manually adjusted torque profiles are presently utilized by the system to counteract gravitational forces, with extensive manual calibration needed for various poses and payloads. The lack of this dynamic adjustment, unlike the feedback-based position and velocity control, impacts the efficiency and versatility of the arm.

5.4.3. Safety-Driven Operational Mode Restriction

The team's primary use of MIT mode for safety reasons limits the exploration of the arm's full capabilities, particularly its force control abilities available in servo mode. While MIT mode provided a safer environment for initial validation, the testing in servo mode allows for direct torque control, essential for tasks like lifting and stable holding. However, operation in servo mode can be dangerous, and if not with the correct testing environment, can harm both the user and the manipulator components. Addressing safety concerns through refined control algorithms and robust safety protocols will be crucial to cautiously and progressively unlock the arm's full potential by enabling thorough testing and utilization of *servo mode.*

5.4.4. External Wiring Constraints

The current external wiring configuration of the robotic arm imposes physical limitations on joint movement and overall arm freedom. The external routing of cables restricts the range of motion for certain joints, preventing the arm from achieving its full potential workspace and limiting its ability to perform complex manipulations that require extensive joint articulation. This external wiring also increases the risk of cable entanglement or damage, potentially compromising the system's reliability and safety.

5.5. Future work

Future work must overcome the limitations outlined above. In accomplishing this, the team suggests the following for a potential direction of future work of other capstone teams. A centralized control architecture with a high-performance controller is needed for real-time control of the kinematics and dynamics of the arm, perhaps with advanced control methods for smooth multi-joint coordination. Implement a gravity compensation routine that accepts the arm's configuration and motor data and dynamically adjusts motor torques so the robot doesn't injure itself. Future design improvements should consider internal wiring alternatives or other cable management schemes to minimize wiring constraints and enhance the arm's range and longevity.

One significant challenge the team encountered was controlling the J5 motor (GL40 Gimbal Motor), which couldn’t connect to the R-link serial-to-USB communication device, preventing control of the fifth joint of the robotic arm. To resolve this, the team consulted the motor manufacturer, CubedMars, and was directed to Elmo Motion Control. After discussing the motor’s intended use as the wrist joint, Elmo recommended the G-DCWHI2.5/100SESQ servo driver and CBL-GDCWHIKIT02 wiring kit. Implementing these products allows future teams to control the gimbal motor and ensure proper functionality of the fifth joint. Successfully integrating the motor requires understanding motion control systems, including configuring servo drivers, CAN bus communication protocols, and wiring design. Using an Arduino with a CAN transceiver like the MCP2515 module enables efficient communication with multiple motors, ensuring synchronization and real-time control by structuring and sending messages. This setup offers scalability, efficiency, and reliability for complex robotic systems, making it essential for controlling several motors in the design.

One key improvement that can be made in the future is creating a comprehensive control system that allows the control of multiple motors at the same time. A control system for the robotic arm can be implemented using an Arduino microcontroller connected via CAN (Controller Area Network) communication. This setup allows for efficient control of multiple motors using a single communication bus, significantly reducing the complexity and bulk of wiring typically required in multi-joint systems. By leveraging the CAN protocol, each motor can be individually addressed and controlled with precise torque, velocity, and position commands. To ensure safe and effective operation, custom Arduino control software can be developed to manage motor coordination, enforce motion limits, and handle real-time feedback.

It is also important that future teams solve safety concerns by having more advanced control algorithms and safety protocols in place to slowly and progressively enable the full functionality of the arm by permitting more thorough testing and utilization of the different applicable motor modes.

6. Acknowledgements

The completion of this project would not have been possible without the support, guidance, and collaboration of several individuals and organizations. The team is deeply appreciative of the time, resources, and expertise generously shared by mentors, sponsors, university staff, and external advisors. Each contribution played a significant role in shaping the development and success of the robotic arm, and the team would like to formally recognize those who made a meaningful impact.

First and foremost, the team would like to thank Dr. David Mascarenas, the project sponsor, for his continuous support and direction throughout the year. His expertise and consistent feedback helped the team stay focused on designing a robotic system that could realistically be used in hazardous environments. His involvement was instrumental to the success of the project.

The team also wishes to acknowledge Dr. Swaroop Darbha for his mentorship during the first semester. His early guidance in systems thinking helped lay a strong foundation and provided clarity in the initial stages of design.

Gratitude is extended to Dr. Ya Wang, who served as the team's second-semester mentor. Her technical insights and ongoing support during the development and testing phases were crucial in refining the design and pushing the project forward.

The team is thankful for the Rapid Prototyping Studio (RPS) in the Mechanical Engineering Building and the Fischer Engineering Design Center (FEDC) for providing tools, equipment, and fabrication support. Their assistance was essential in prototyping and 3D printing the components that brought our design from concept to reality.

Finally, the team would like to recognize Zachry Bucknor-Smartt, a mechanical engineering student at Texas A&M, along with Vidur Simmerman, a research engineer at the Robotics and Automation Design Lab. Both provided valuable technical feedback and design advice throughout the project. Their experience played a major role in improving the arm's mechanical structure and overall performance.

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8. 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. Mascarenas 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 organizes 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

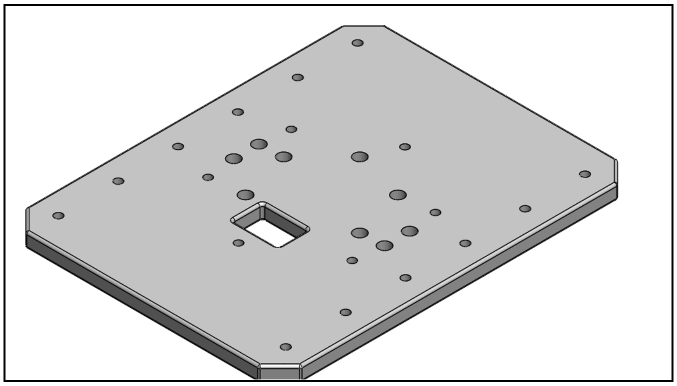


Figure D-1: Robot Base

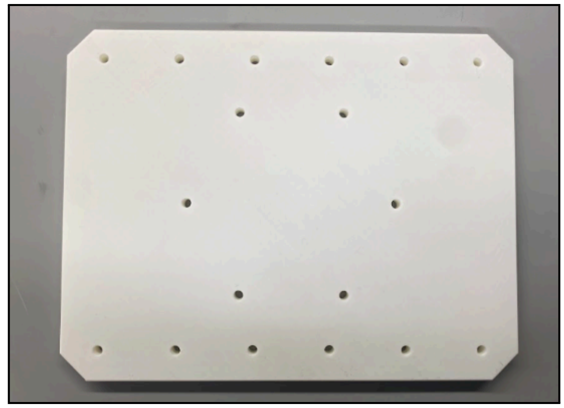


Figure D-2: Robot Prototyped Base

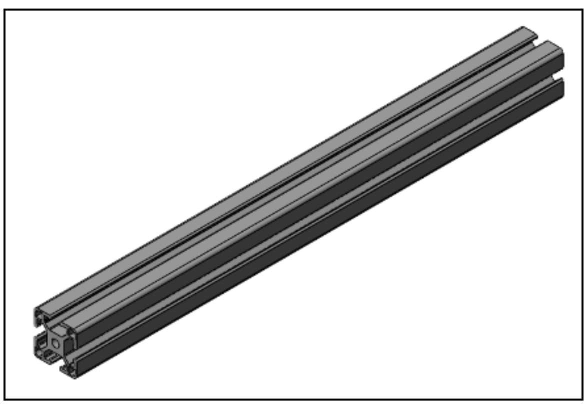


Figure D-3: Aluminum Extrusion (6575N202)

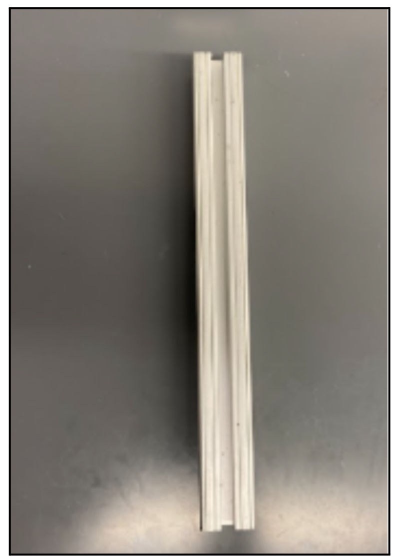


Figure D-4: Aluminum Extrusion (6575N202)

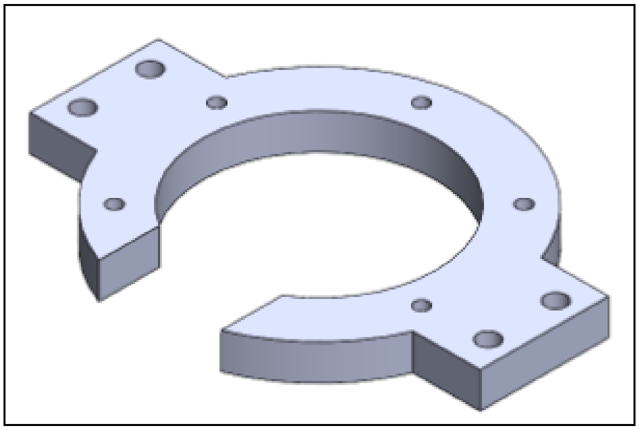


Figure D-5: J1 Motor Holder

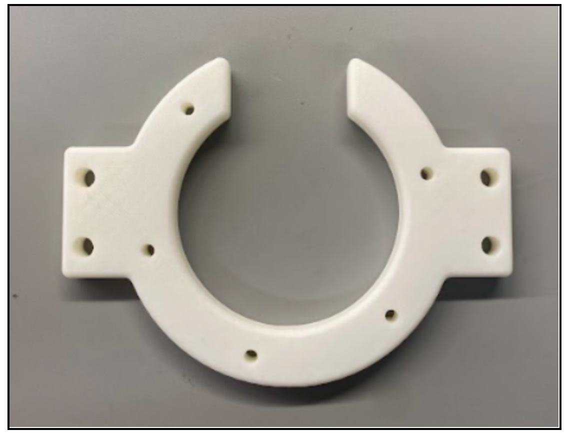


Figure D-6: Prototyped J1 Motor Holder

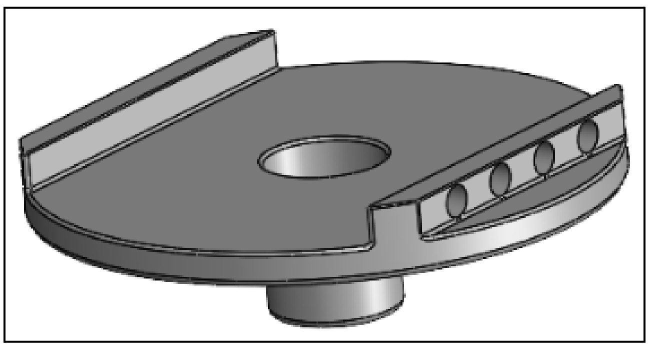


Figure D-7: J1 Mushroom Cap

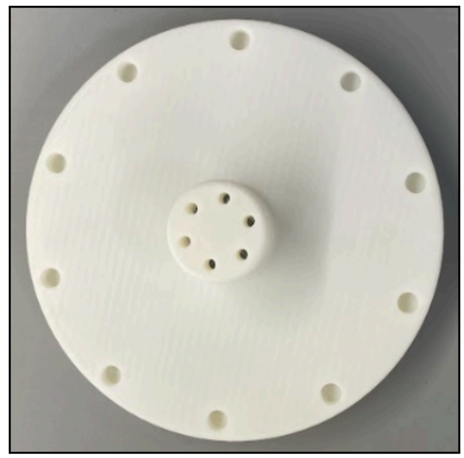


Figure D-8: Prototyped J1 Mushroom Cap

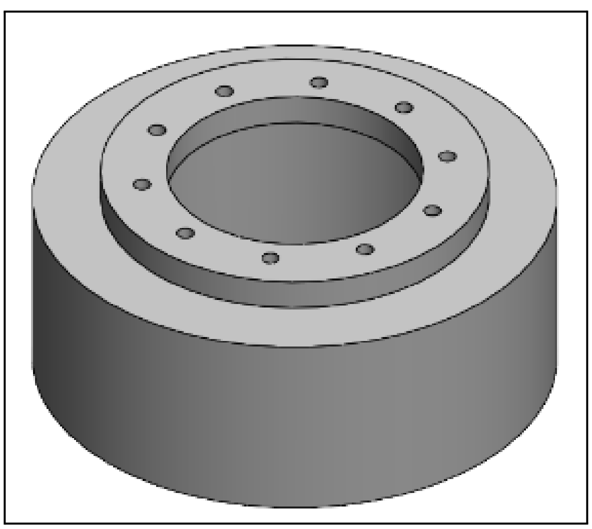


Figure D-9: J1 Motor Cover

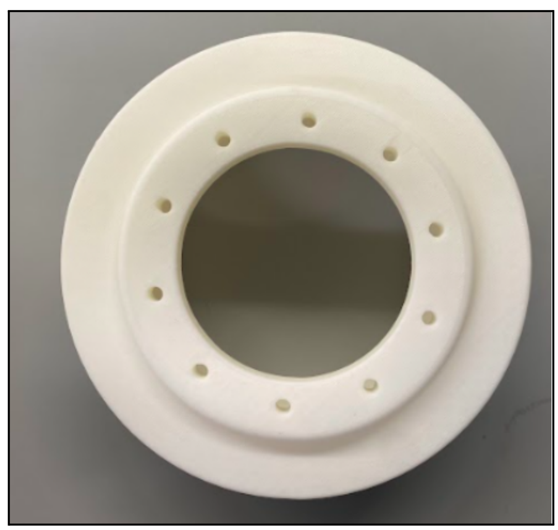


Figure D-10: Prototyped J1 Motor Cover

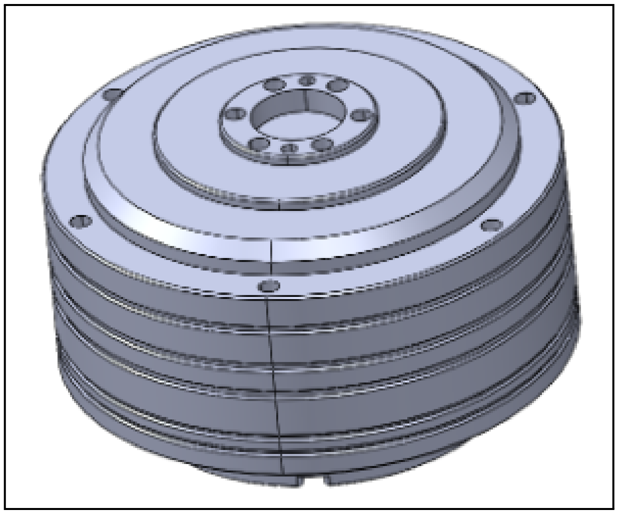


Figure D-11: J1 Motor (AK10-9 V2-0)

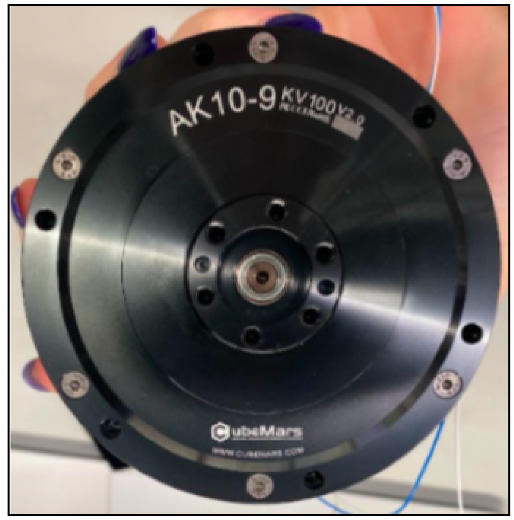


Figure D-12: J1 Motor (AK10-9 V2-0)

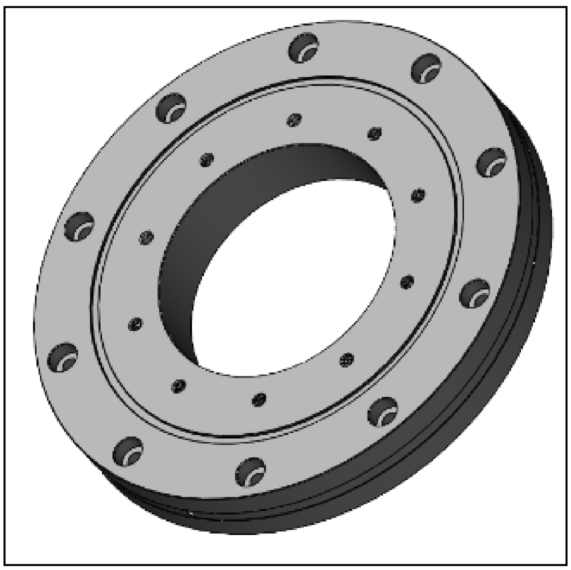


Figure D-13: J1 Cross Roller Bearing (2010N16) (2010N16)

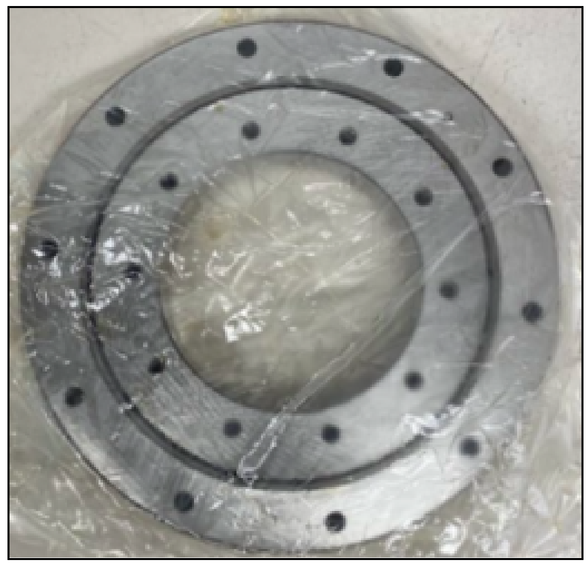
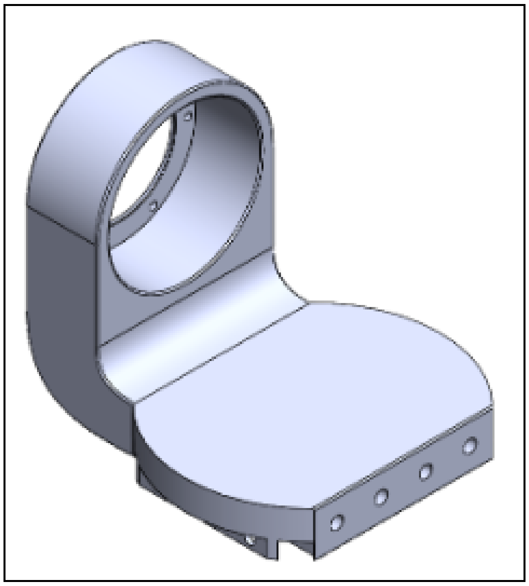


Figure D-14: J1 Cross Roller Bearing



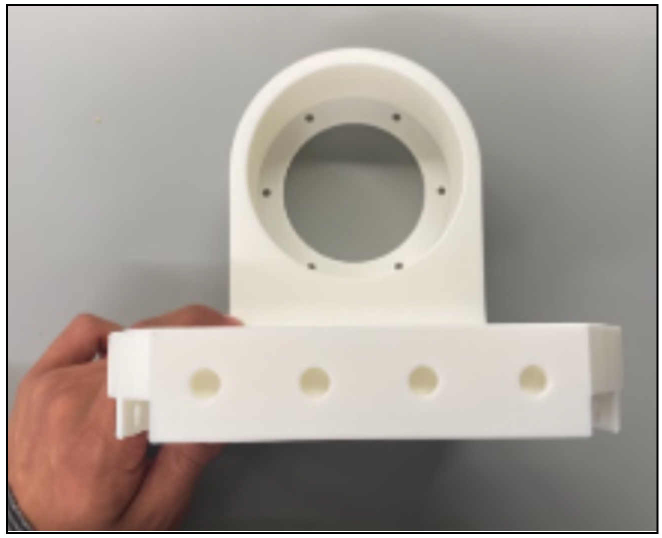
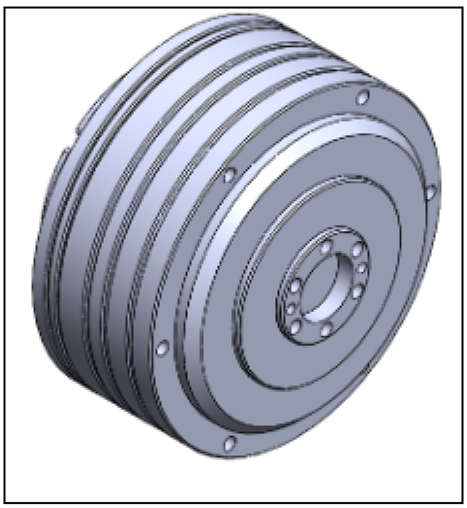


Figure D-15: J2 Motor Holder

Figure D-16: Prototyped J2 Motor Holder



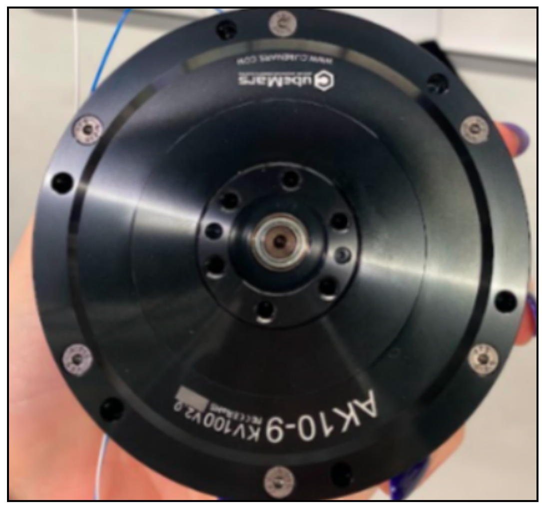


Figure D-17: J2 Motor (AK10-9 V2-0)

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

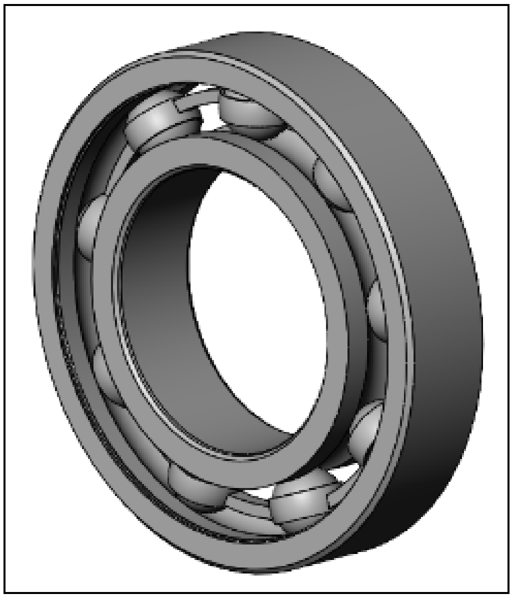


Figure D-19: J2 Ball Bearing (K972K3)

Figure D-20: J2 Ball Bearing (K972K3)

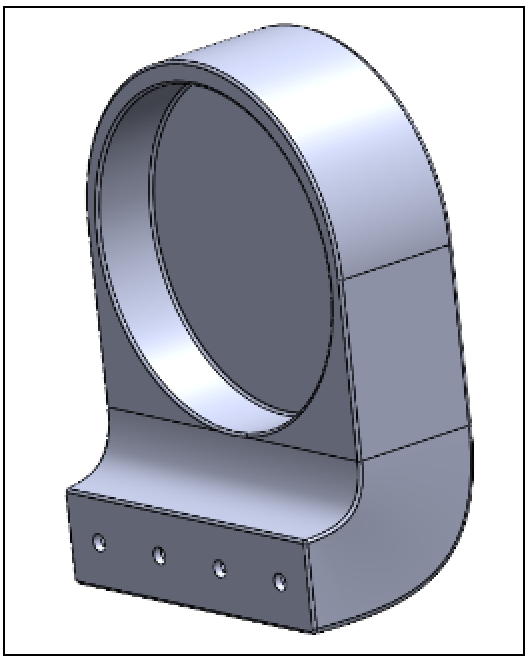


Figure D-21: J2 Bearing Holder

Figure D-22: J2 Bearing Holder (K972K3)

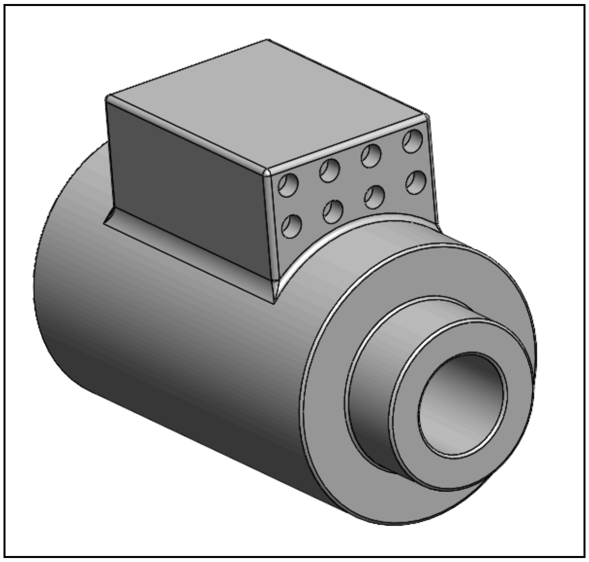


Figure D-23: J2 Cylinder

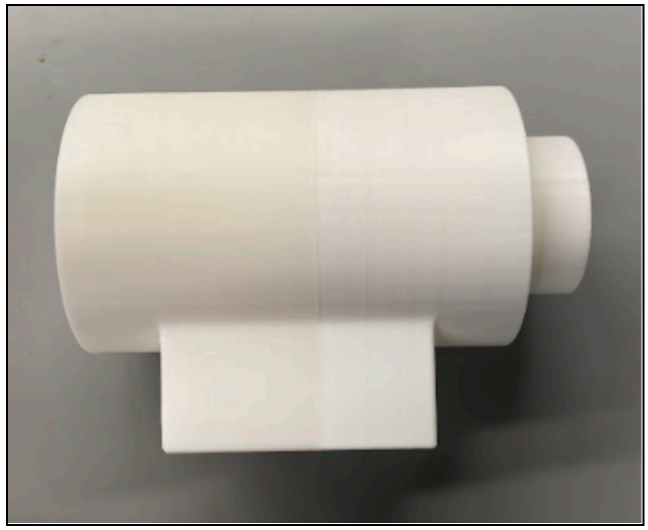


Figure D-24: Prototyped J2 Cylinder

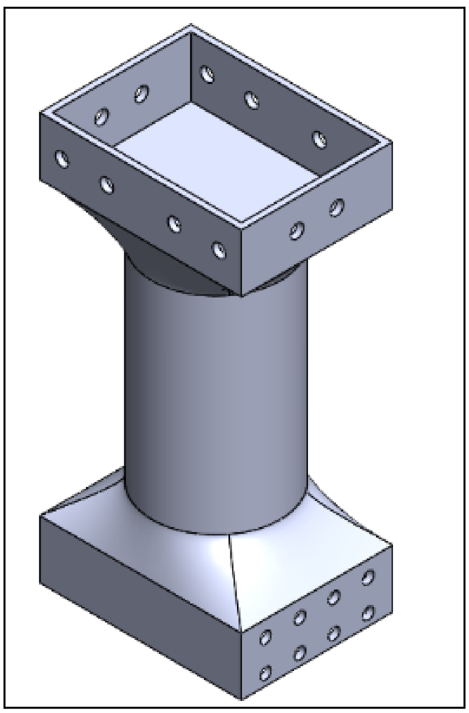


Figure D-25: Bicep

Figure D-26: Bicep

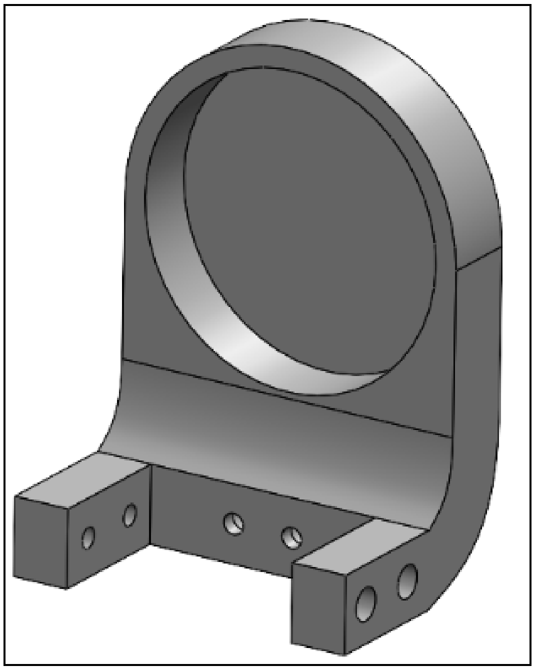


Figure D-27: J3 Bearing Holder

Figure D-28: Prototyped J3 Bearing Holder

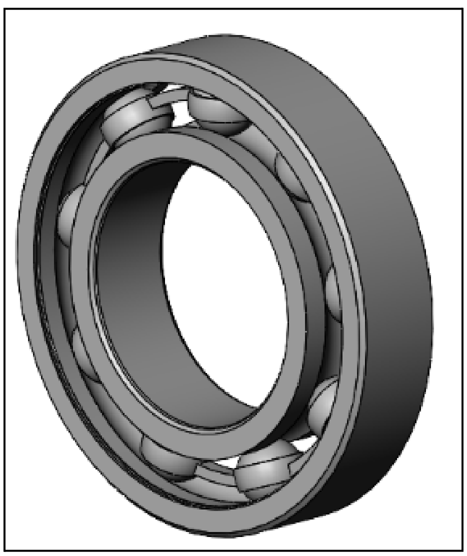


Figure D-29: J3 Ball Bearing (5972K113)

Figure D-30: Prototyped J3 Ball Bearing

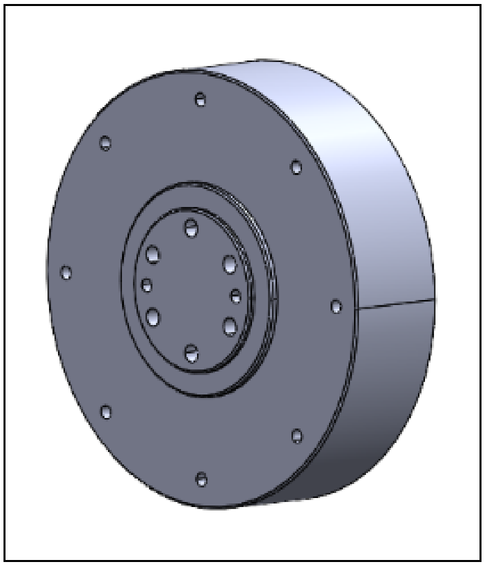


Figure D-31: J3 Motor (AK80-6 & AK80-9)

Figure D-32: J3 Motor (AK80-6 & AK80-9)

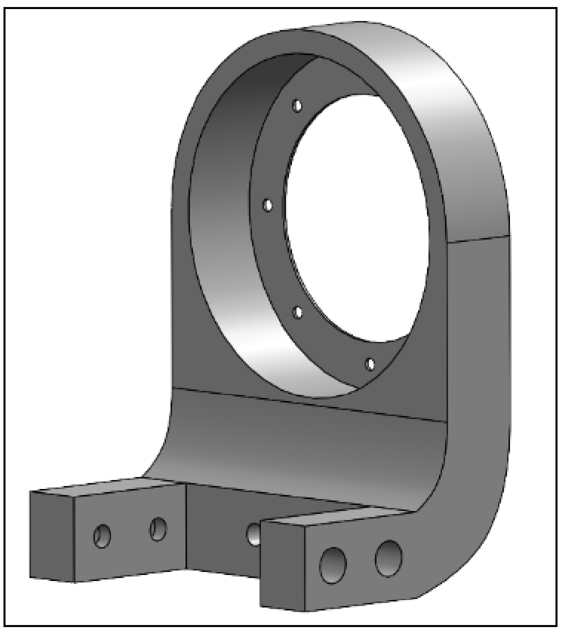


Figure D-33: J3 Motor Holder

Figure D-34: Prototyped J3 Motor Holder

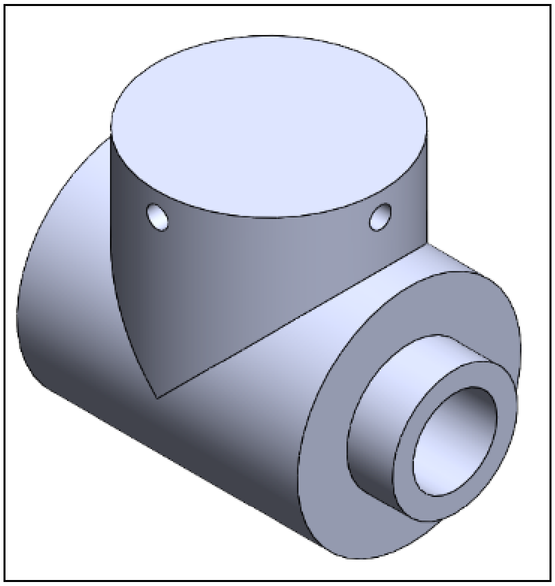


Figure D-35: J3 Motor Holder

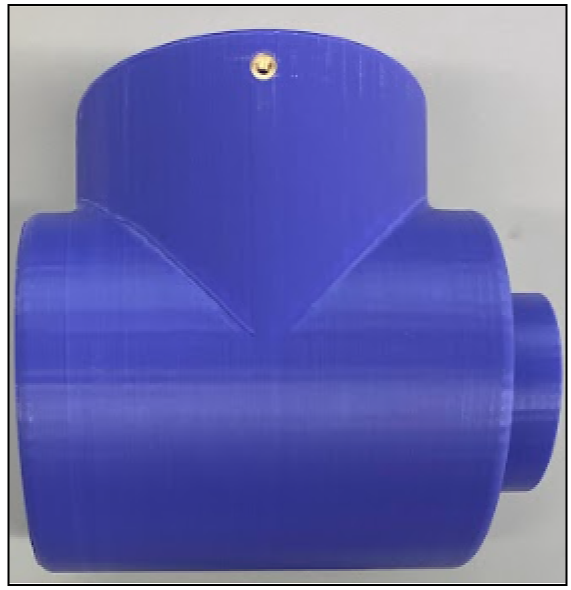


Figure D-36: Prototyped J3 Motor Holder

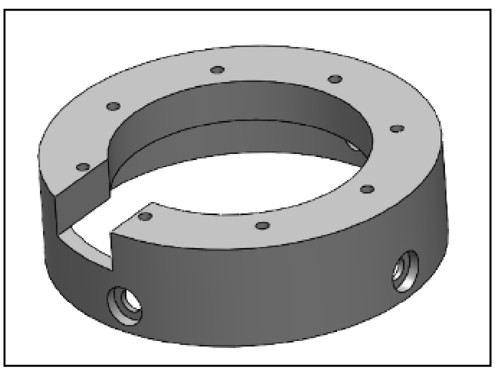


Figure D-37: J4 Motor Holder

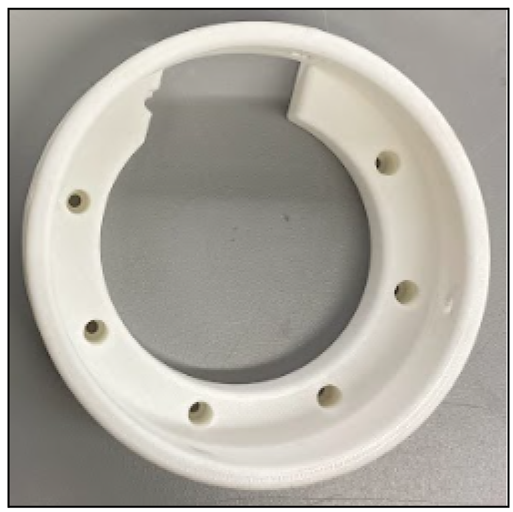


Figure D-38: Prototyped J4 Motor Holder

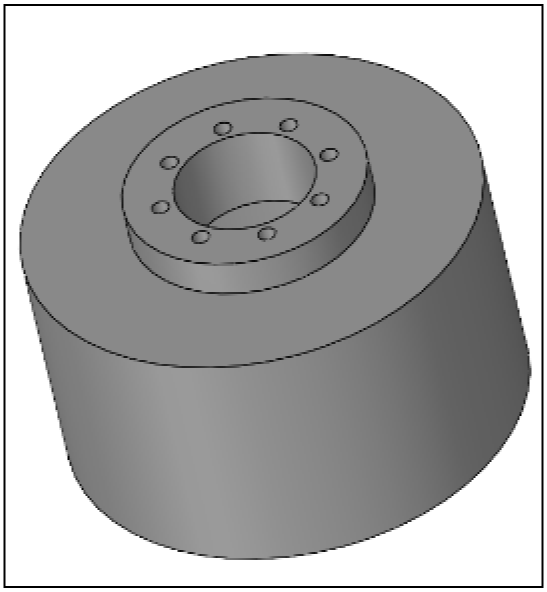


Figure D-39: J4 Motor Cover

Figure D-40: Prototyped J4 Motor Cover

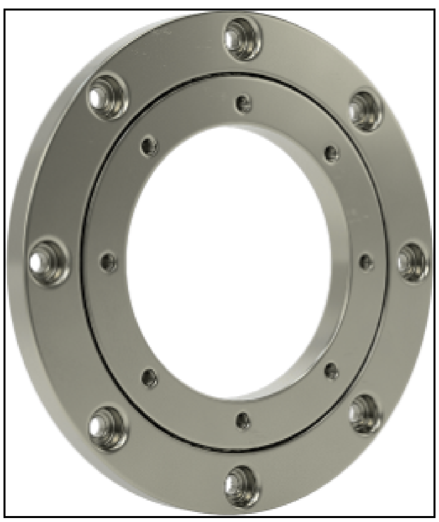


Figure D-41: J4 Cross Roller Bearing (2010N14)

Figure D-42: J4 Cross Roller Bearing (2010N14)

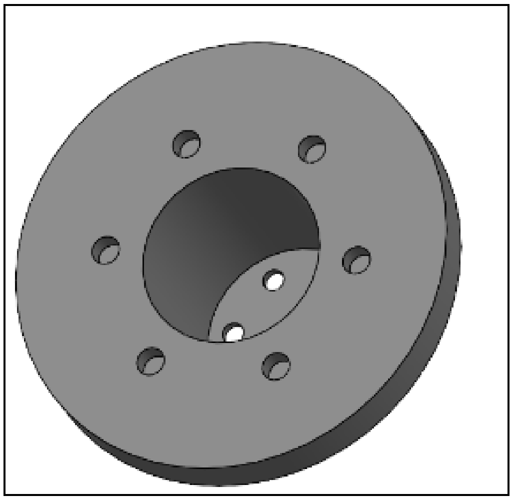


Figure D-43: J4 Mushroom Cap

Figure D-44: Prototyped J4 Mushroom Cap

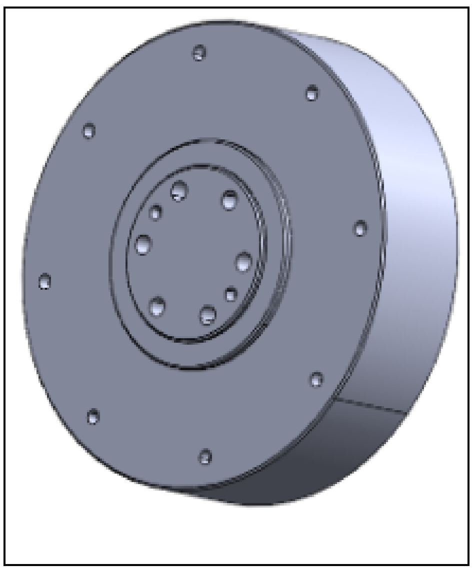


Figure D-45: J4 Motor (AK80-6)

Figure D-46: J4 Motor (AK80-6)

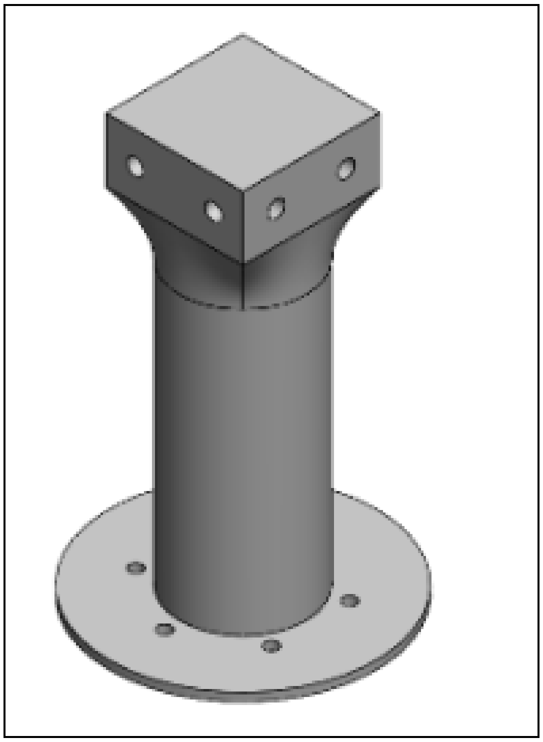


Figure D-47: Forearm

Figure D-48: Prototyped Forearm

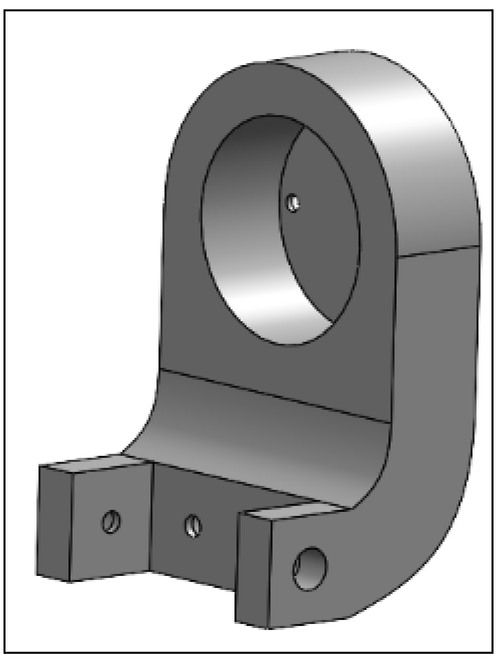


Figure D-49: J5 Motor Holder

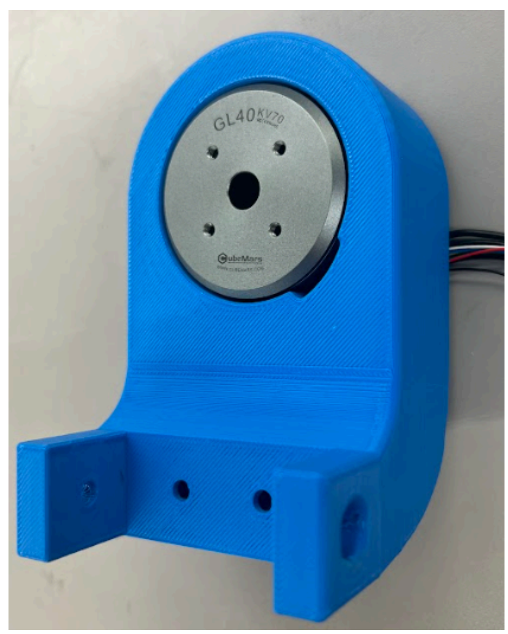


Figure D-50: Prototyped J5 Motor Holder

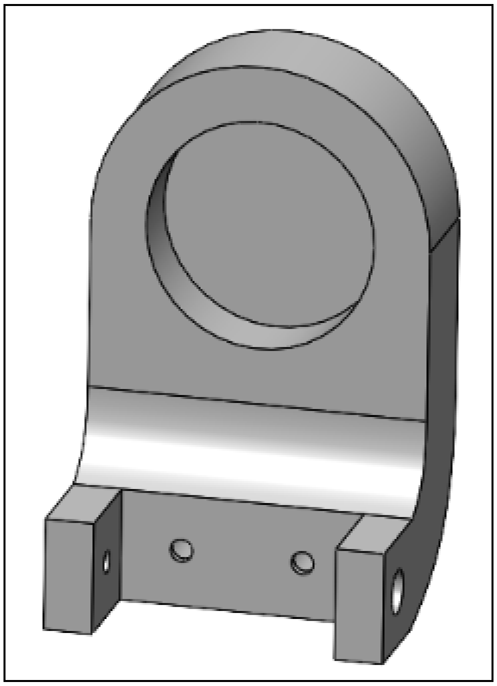


Figure D-51: J5 Bearing Holder

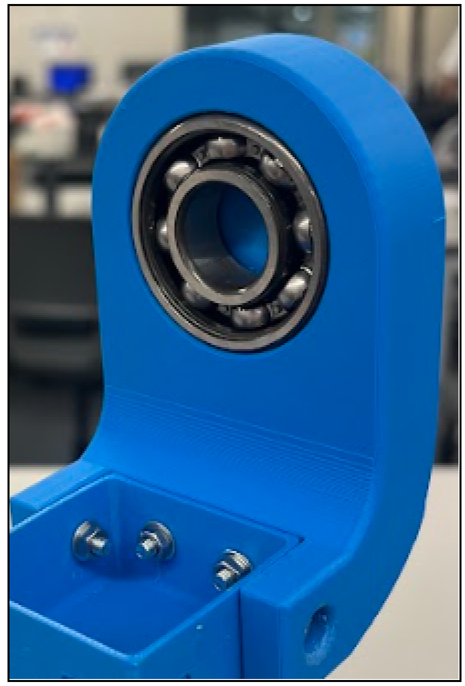


Figure D-52: Prototyped J5 Bearing Holder

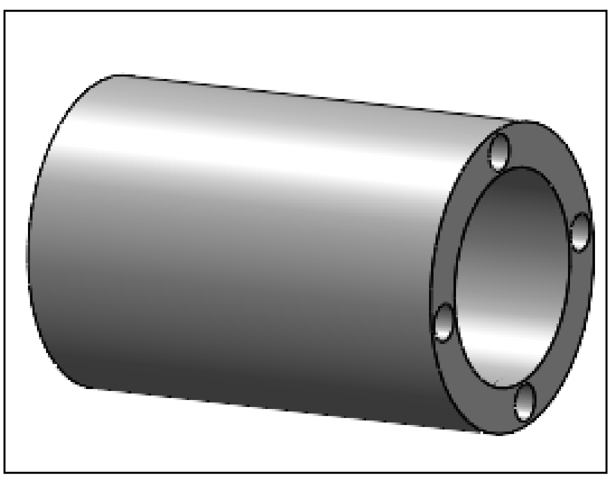


Figure D-53: J5 Cylinder

Figure D-54: Prototyped J5 Cylinder

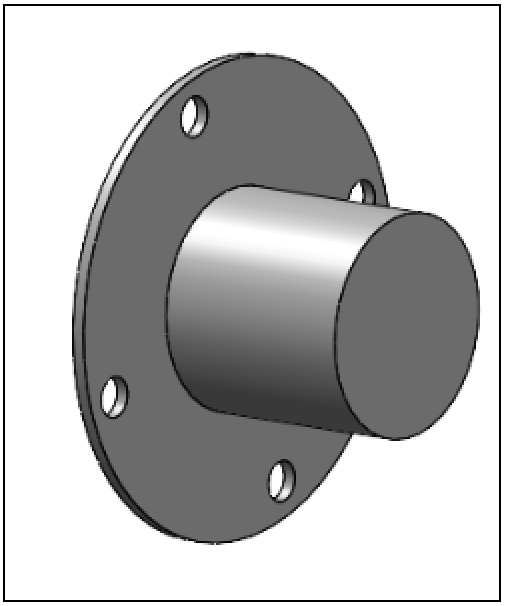


Figure D-55: J5 Cylinder Cap

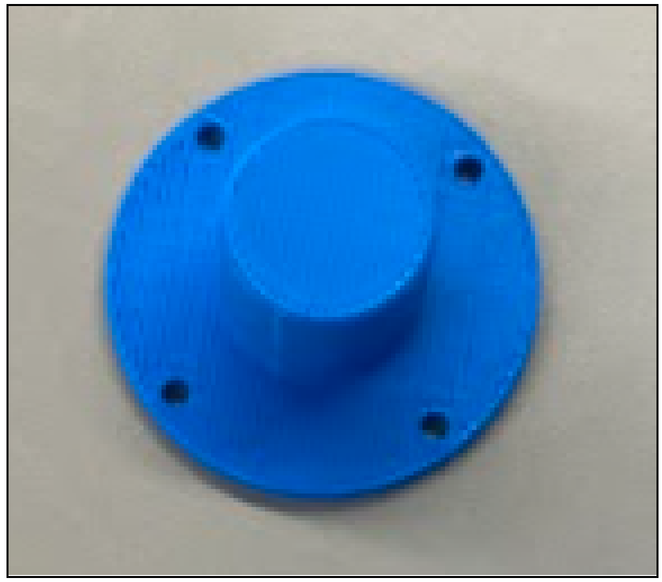


Figure D-56: J5 Cylinder Cap

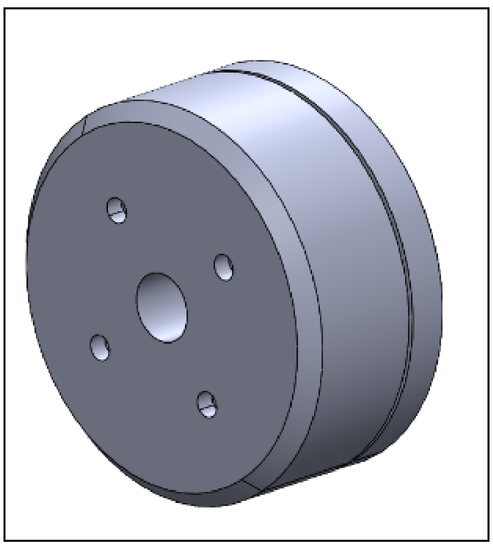


Figure D-57: J5 Motor (GL40)

Figure D-58: J5 Motor (GL40)

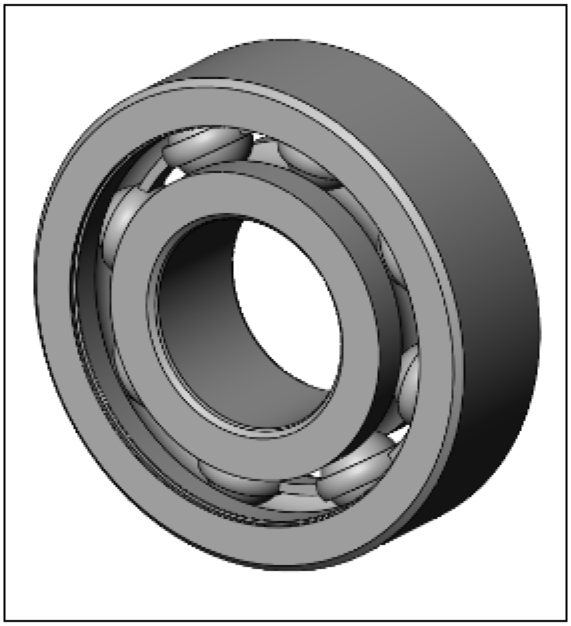


Figure D-59: J5 Bearing (5972K105)

Figure D-60: J5 Bearing (5972K105)

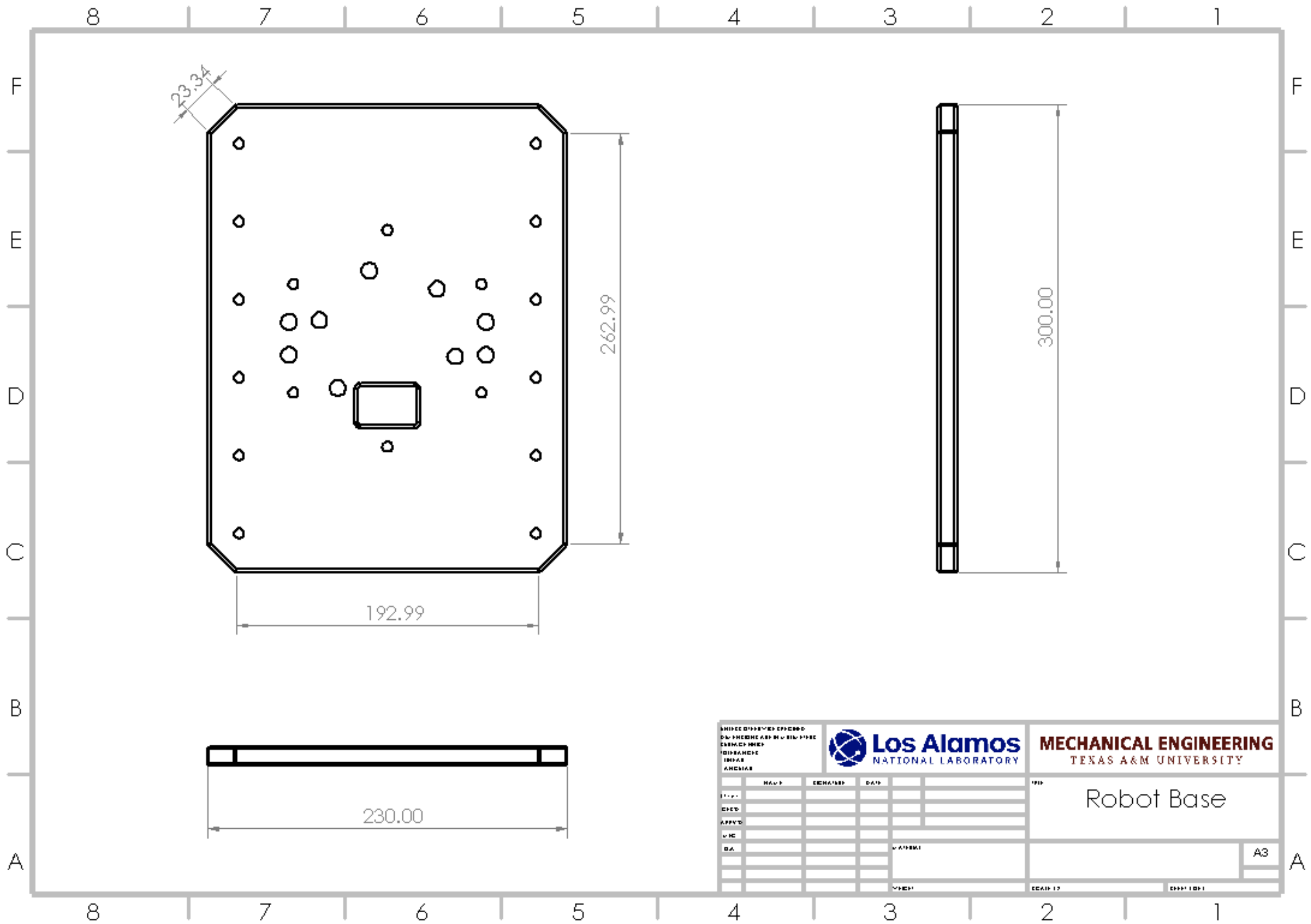


Figure E-1: Robot Base Engineering Drawing

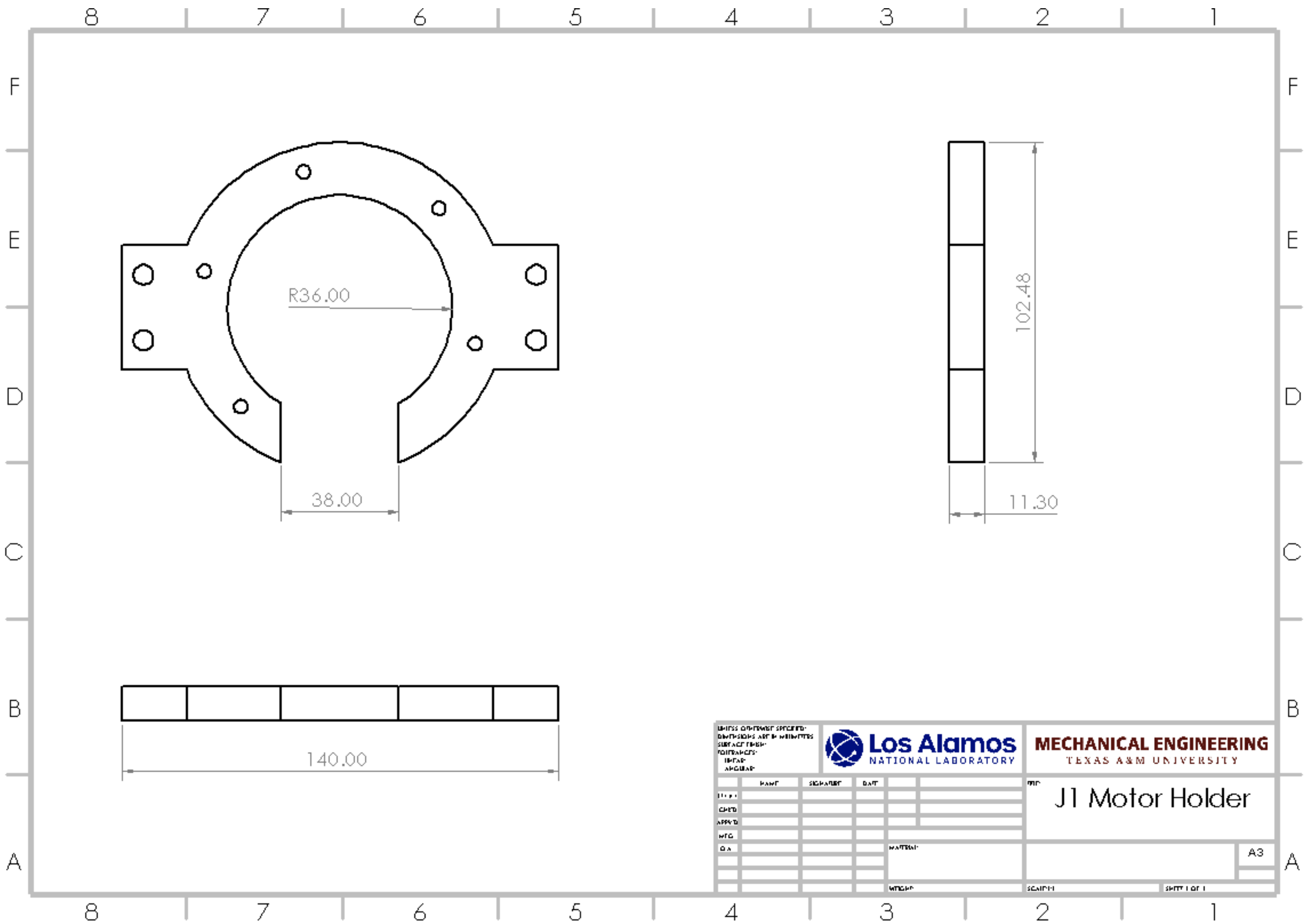


Figure E-2: J1 Motor Holder Engineering Drawing

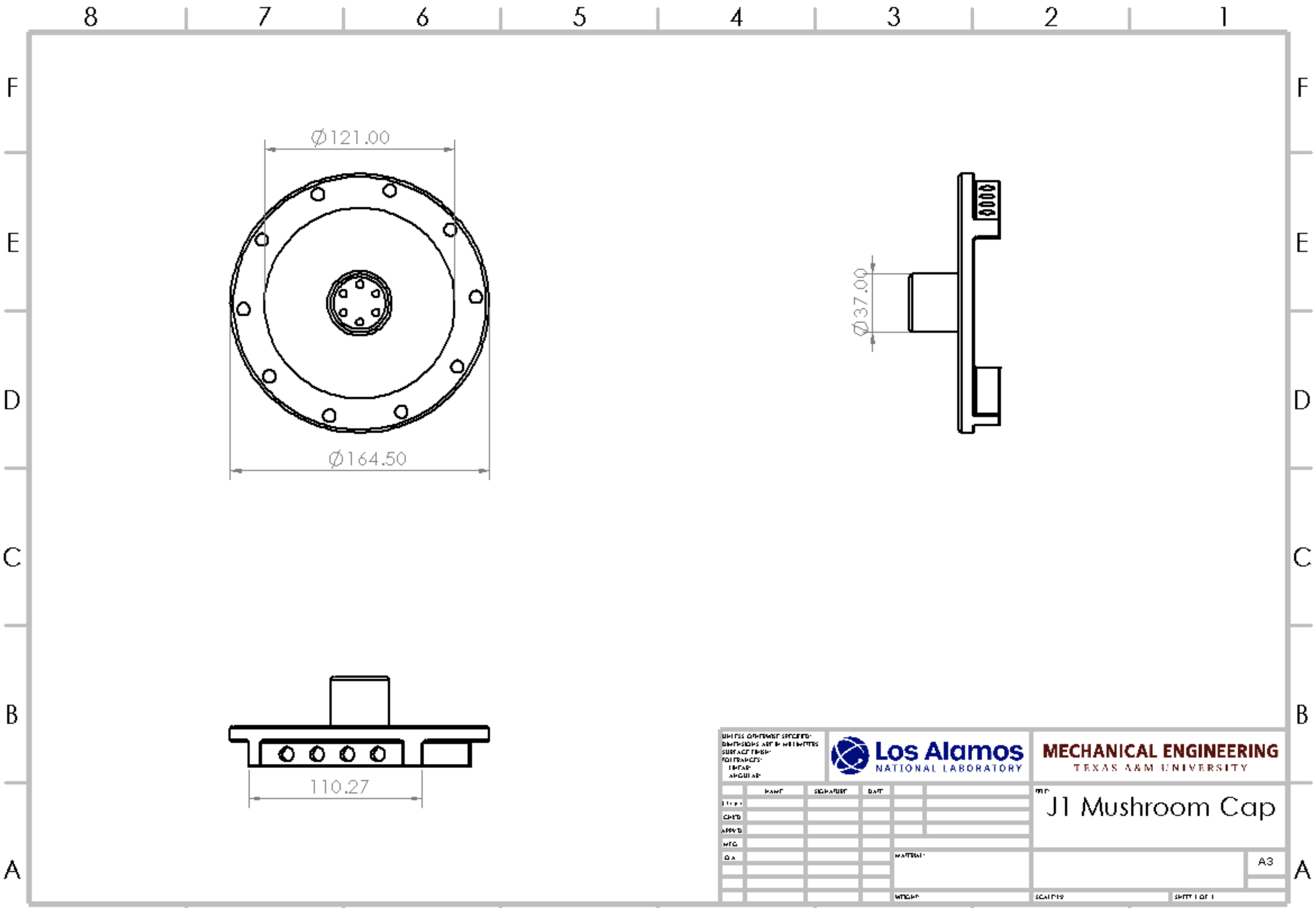


Figure E-3: J1 Mushroom Cap Engineering Drawing

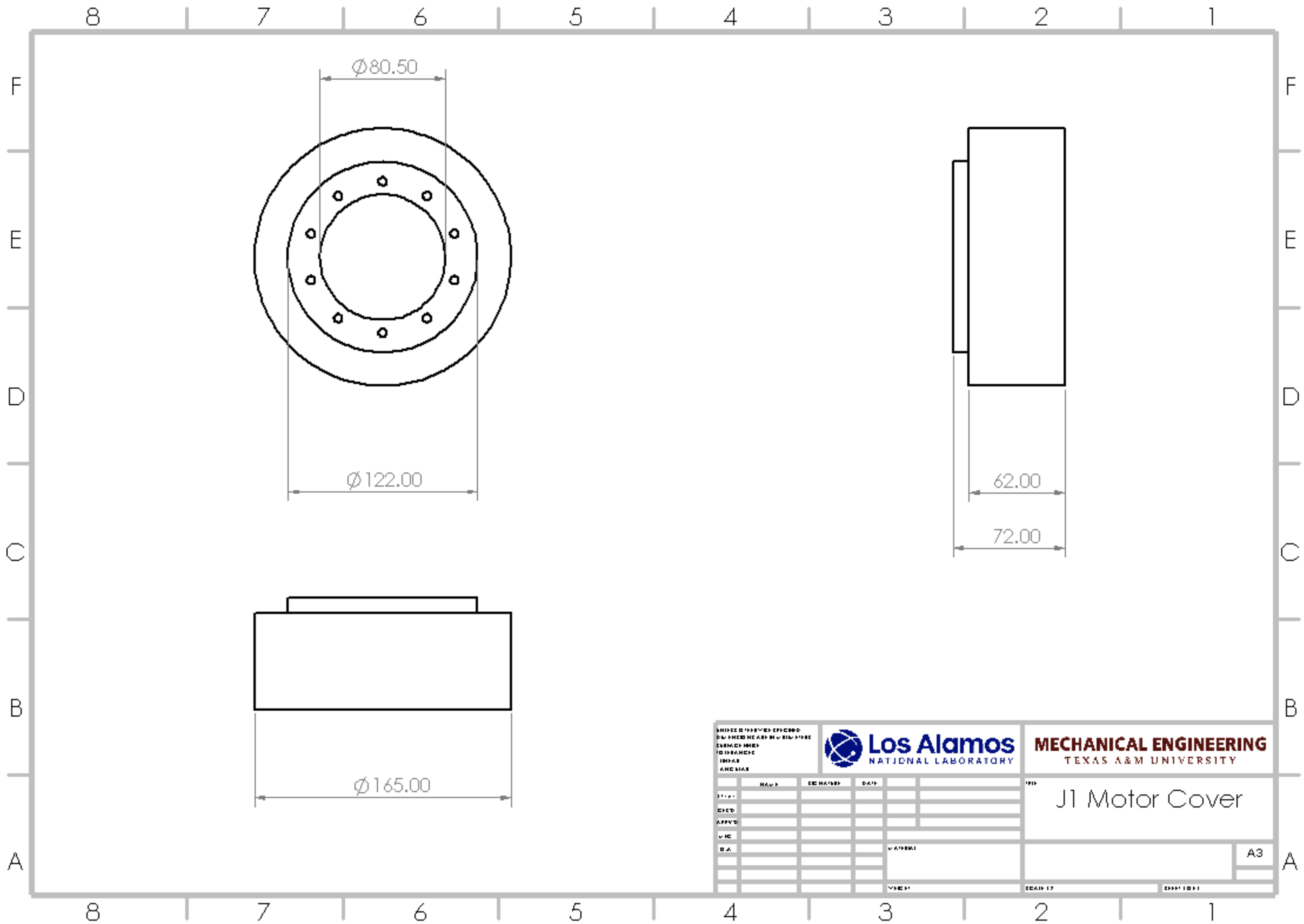


Figure E-4: J1 Motor Cover Engineering Drawing

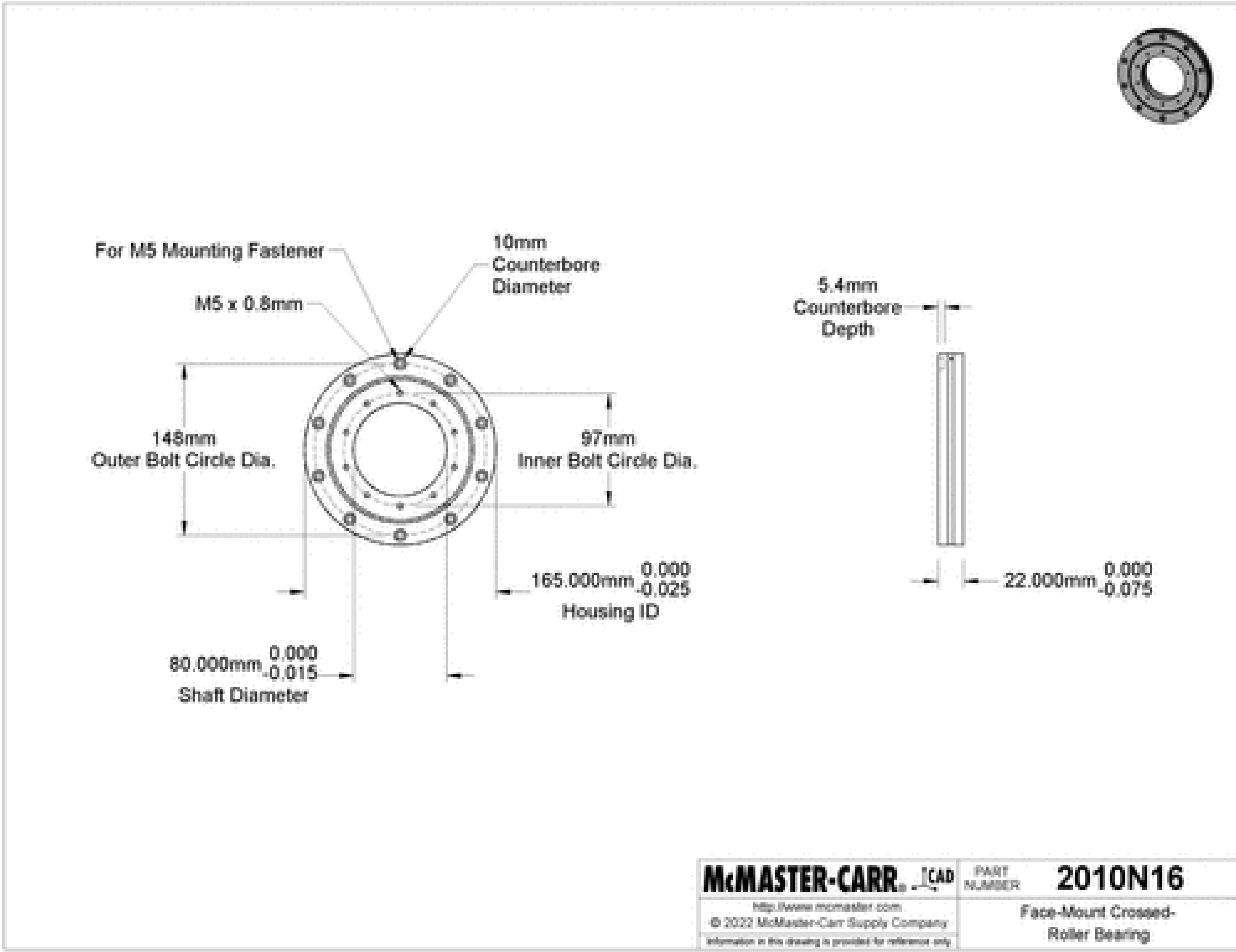


Figure E-5: J1 Cross Roller Bearing Engineering Drawing

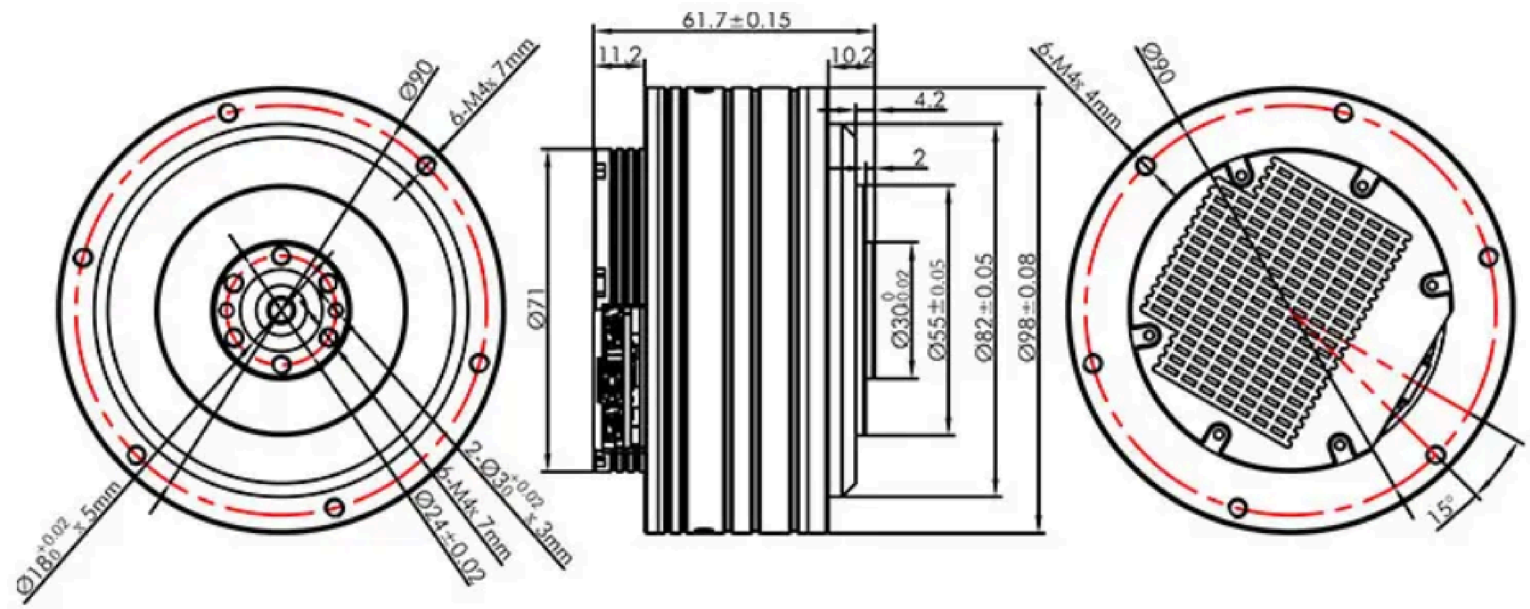


Figure E-6: J1 and J2 Motor Engineering Drawing

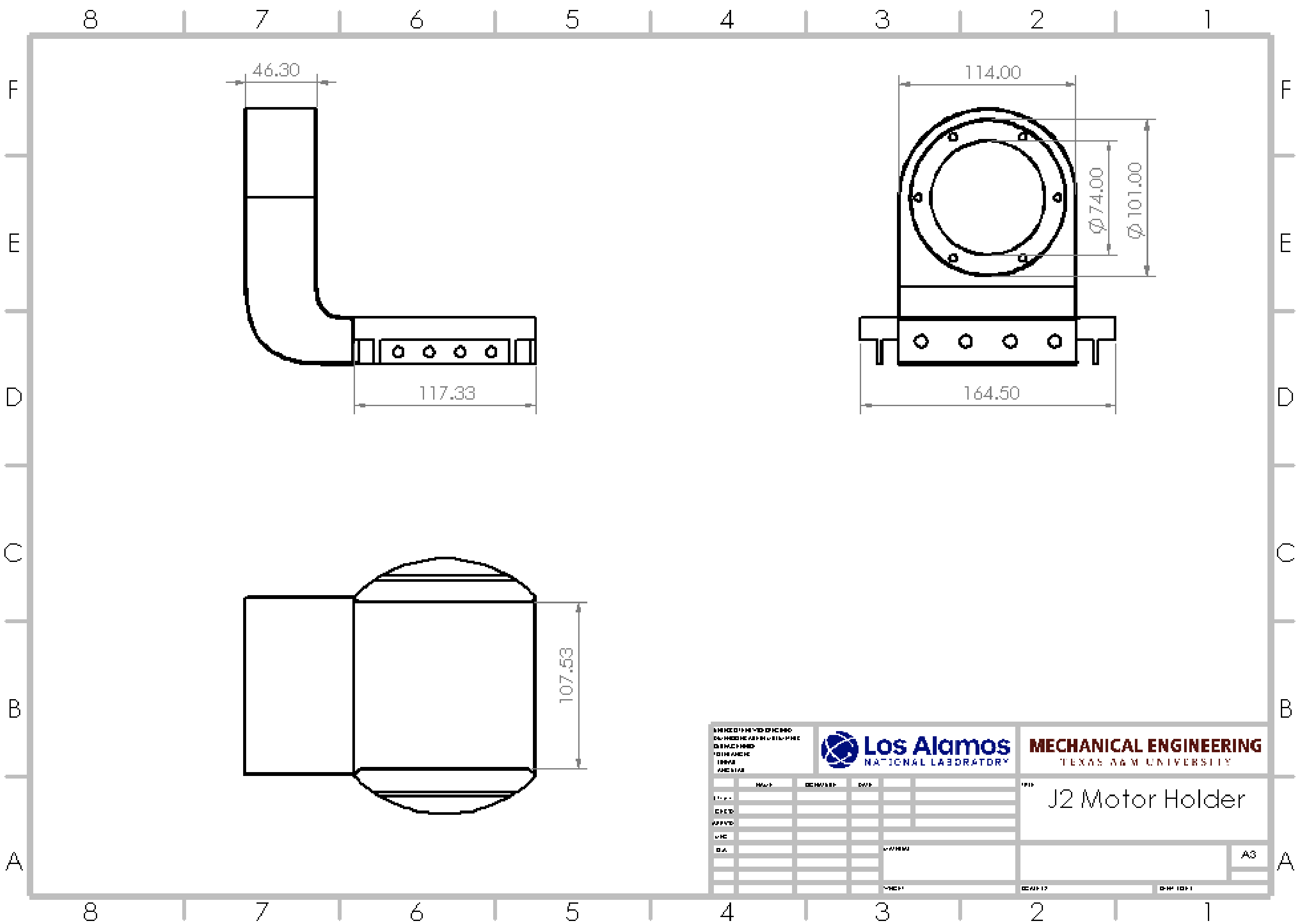


Figure E-7: J2 Motor Holder Engineering Drawing

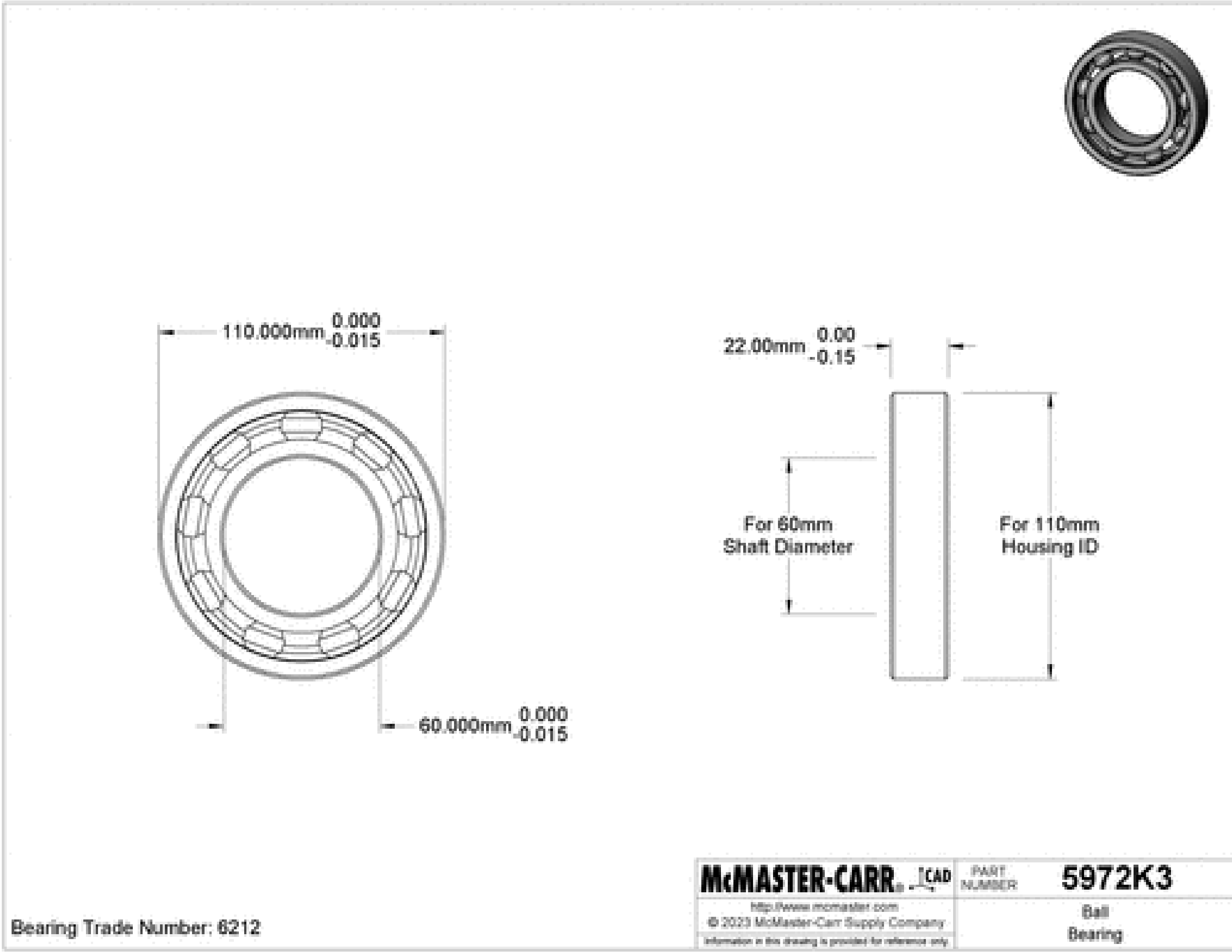


Figure E-8: J2 Ball Bearing Engineering Drawing

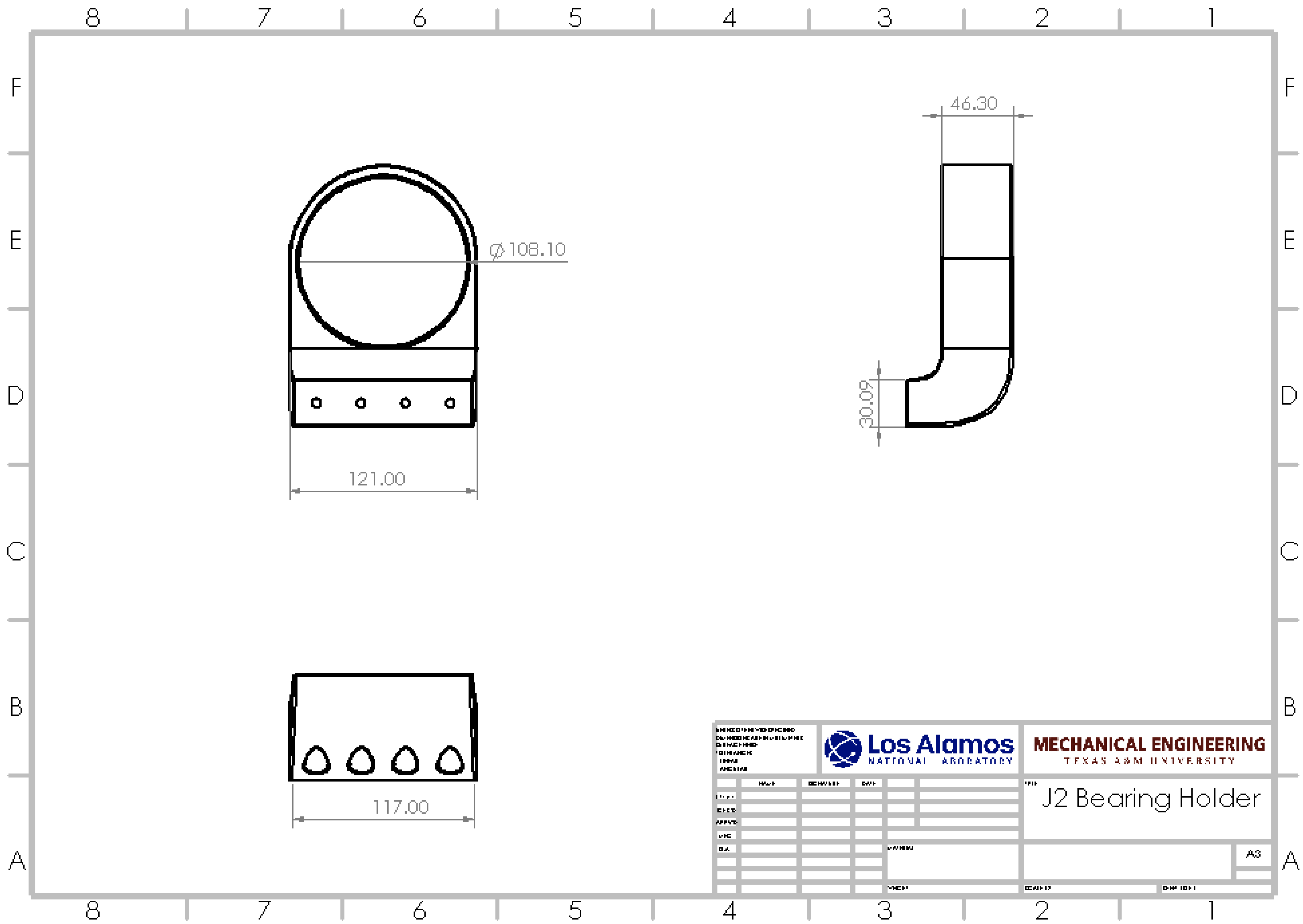


Figure E-9: J2 Bearing Holder Engineering Drawing

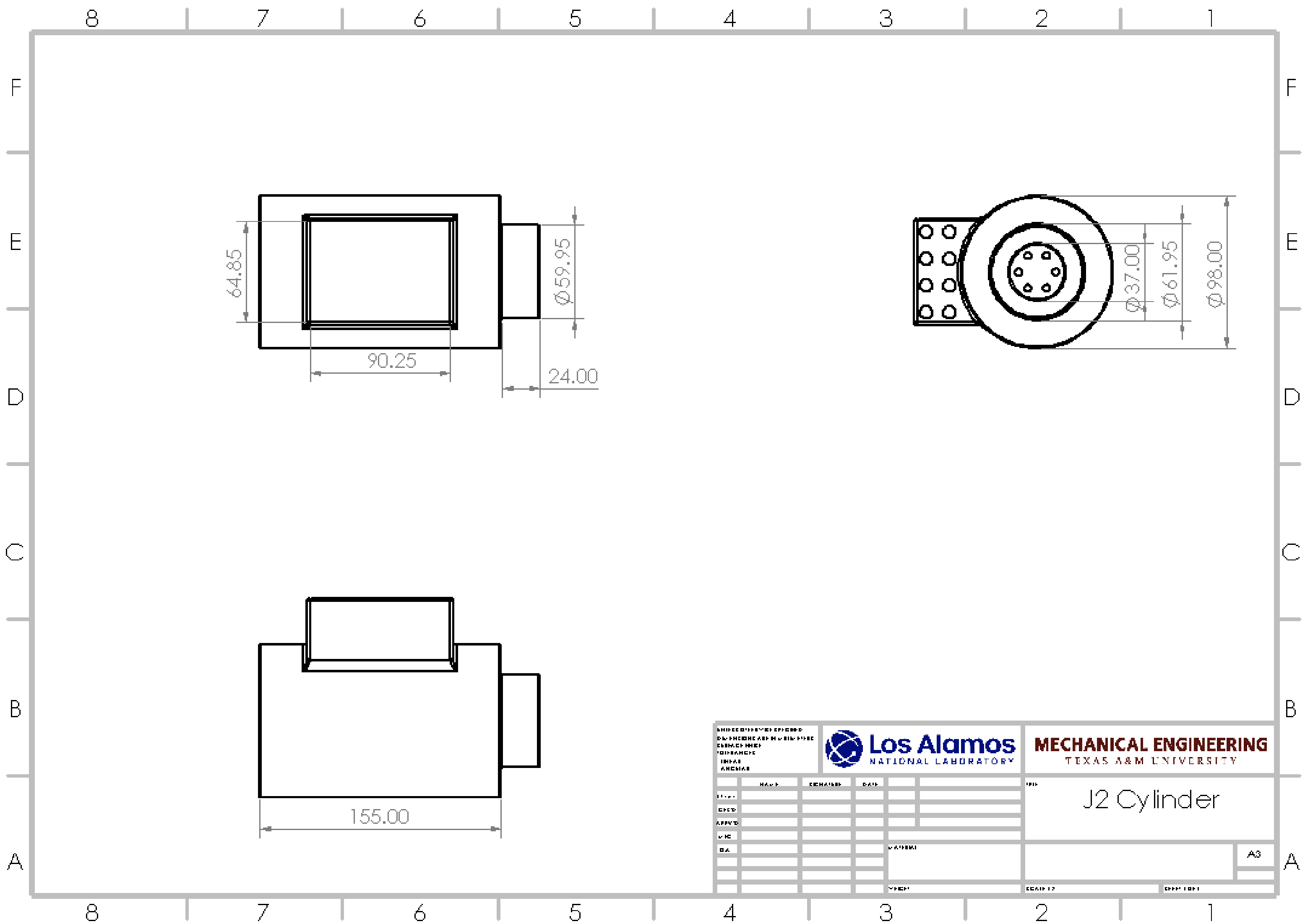


Figure E-10: J2 Cylinder Engineering Drawing

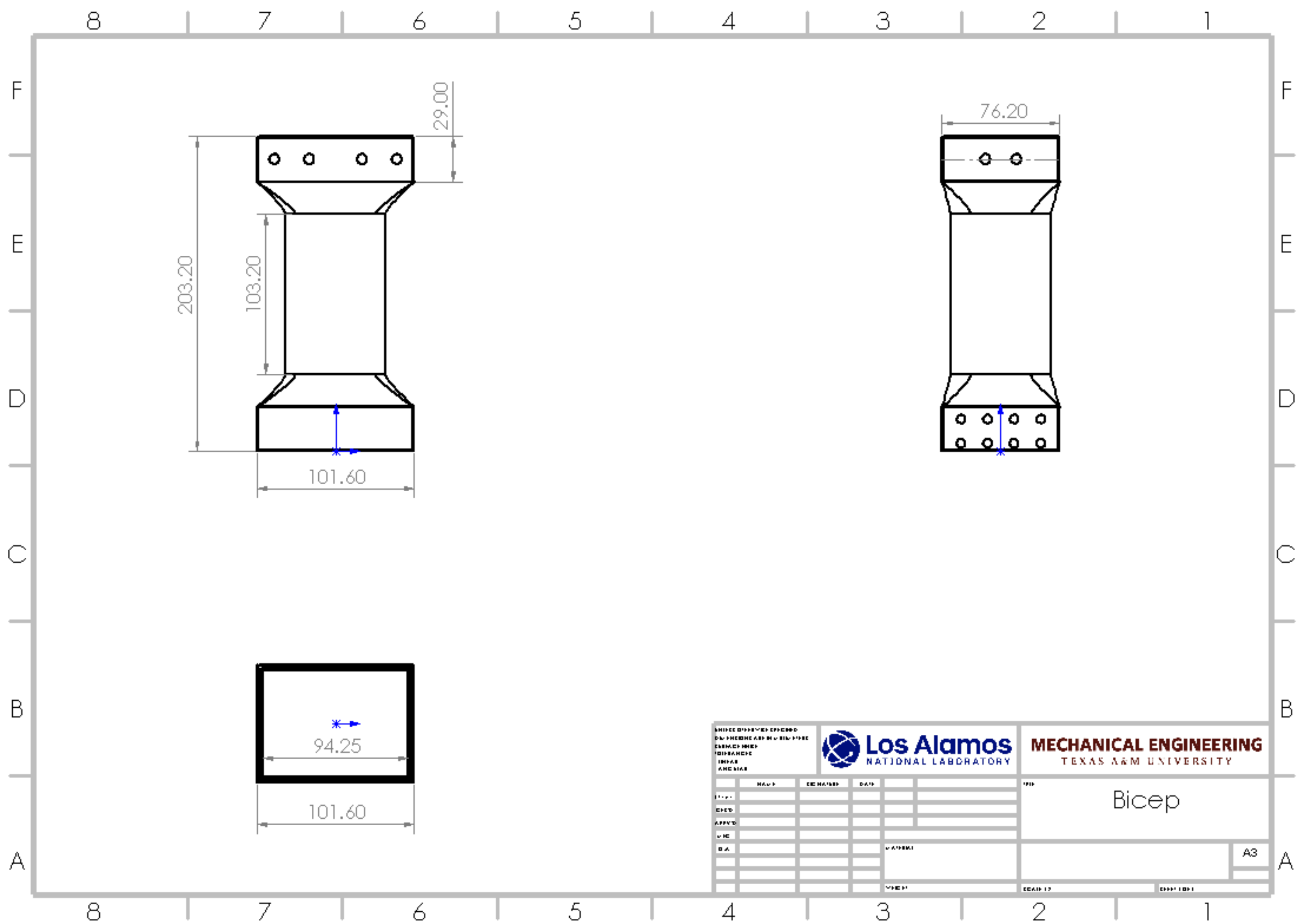


Figure E-11: Bicep Engineering Drawing

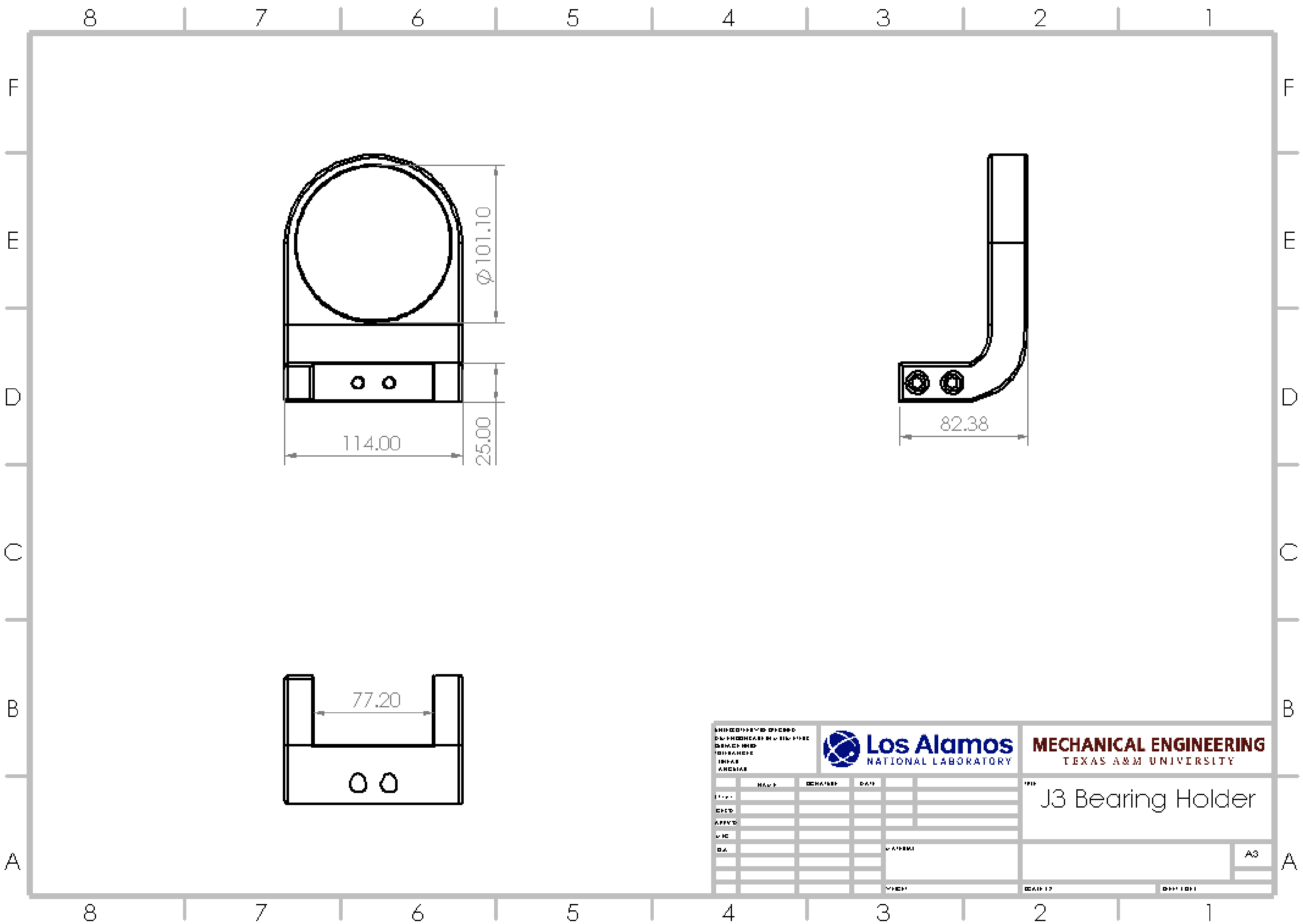


Figure E-12: J3 Bearing Holder Engineering Drawing

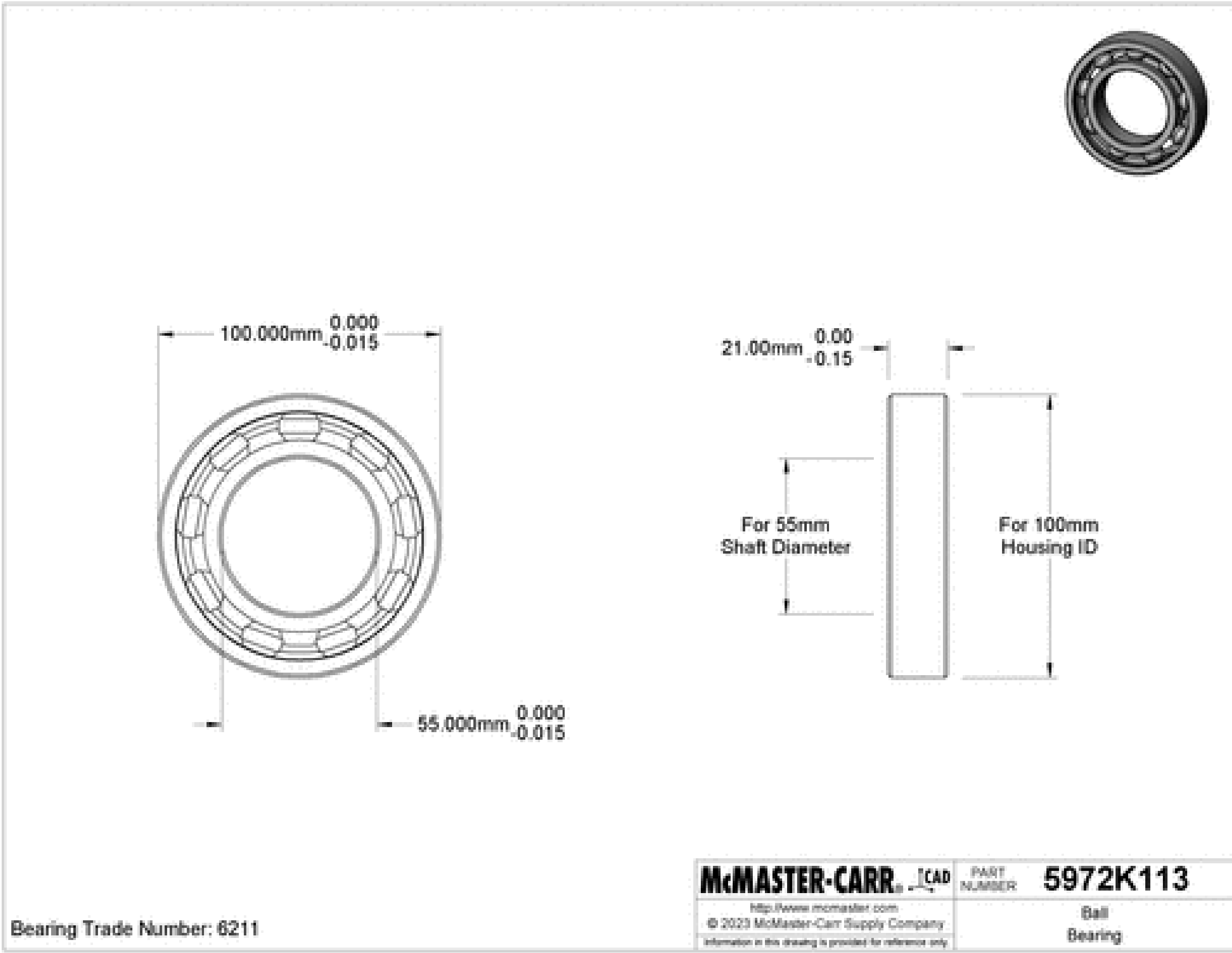


Figure E-13: J3 Ball Bearing Engineering Drawing

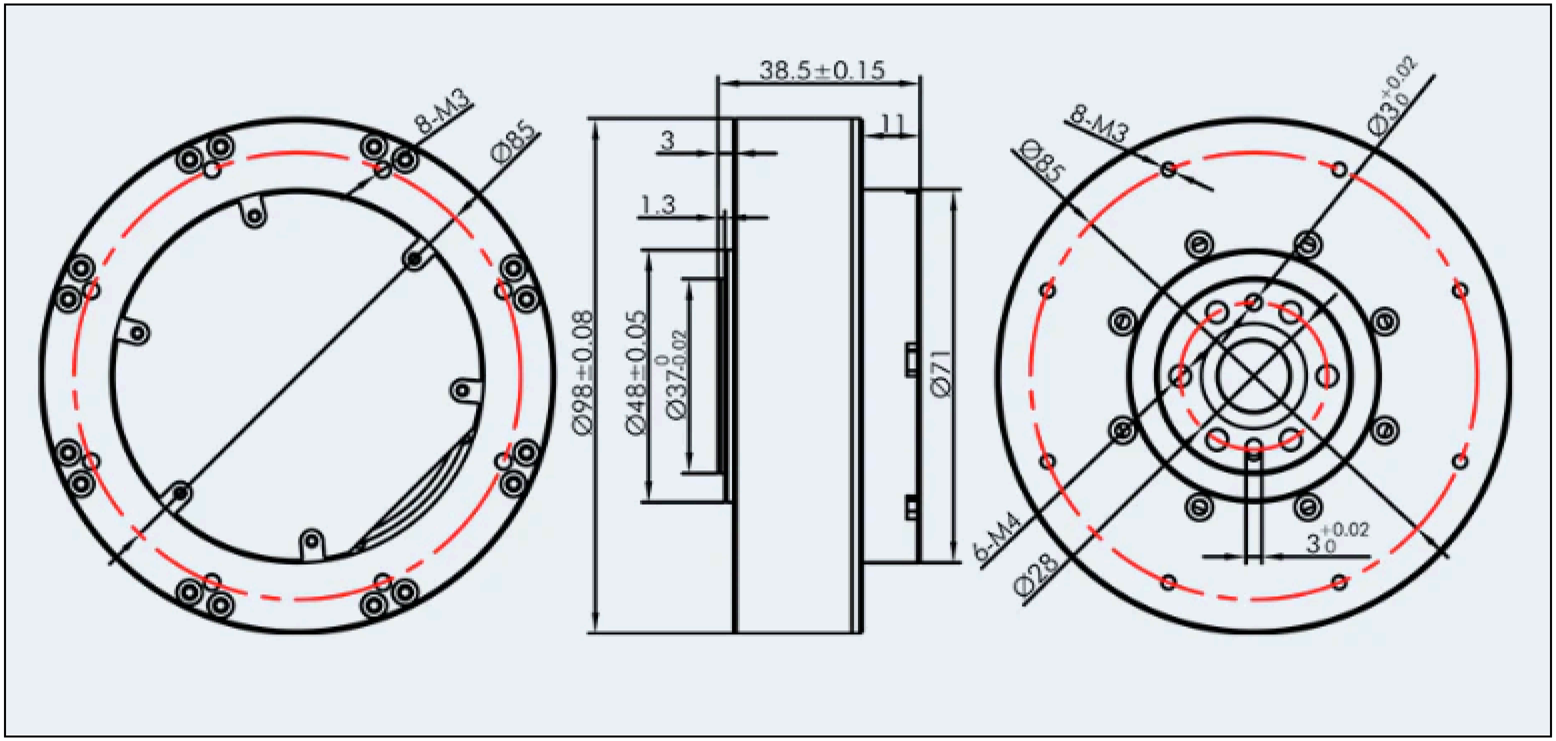


Figure E-14: J3 and J4 Motor Engineering Drawing

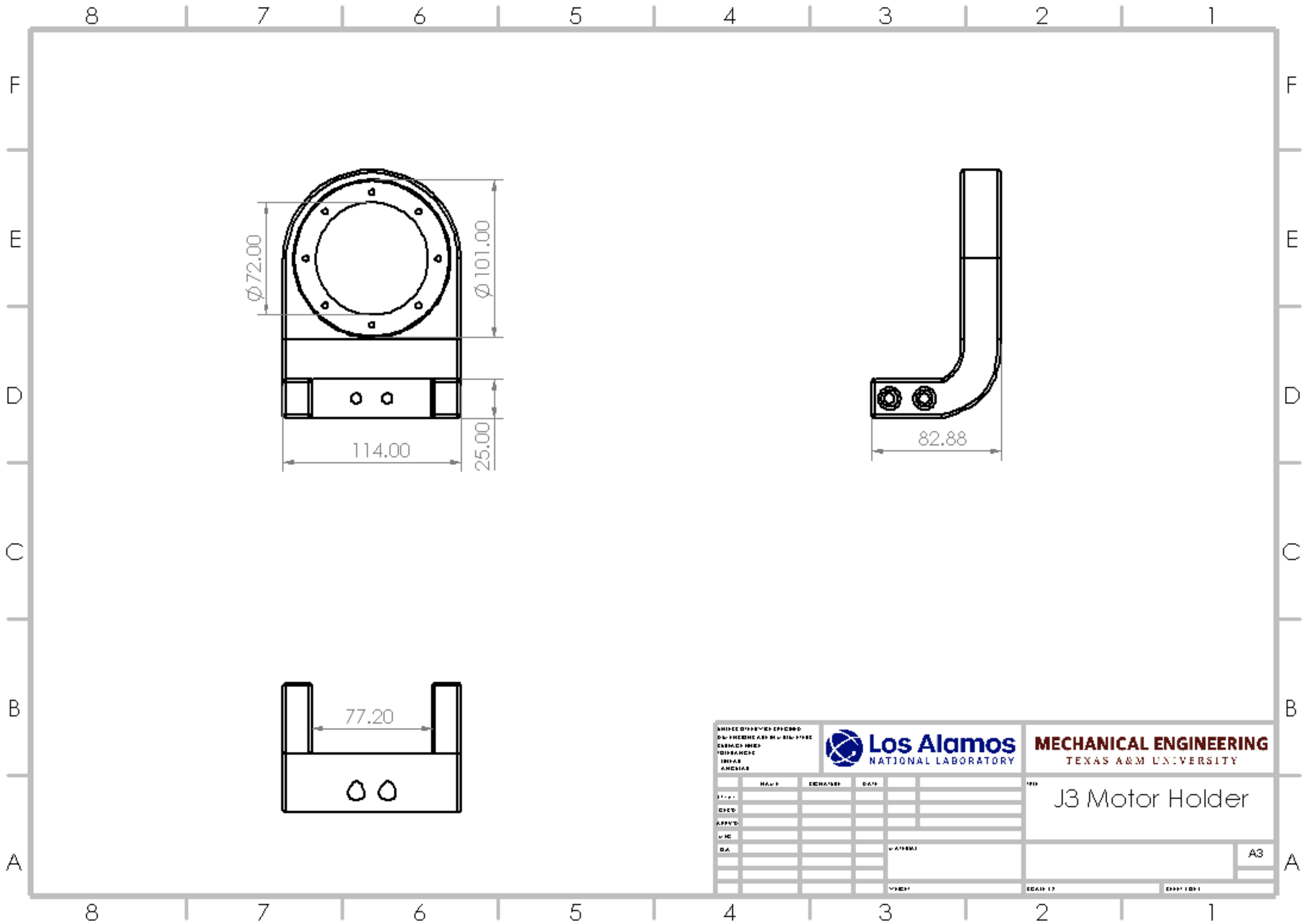


Figure E-15: J3 Motor Holder Engineering Drawing

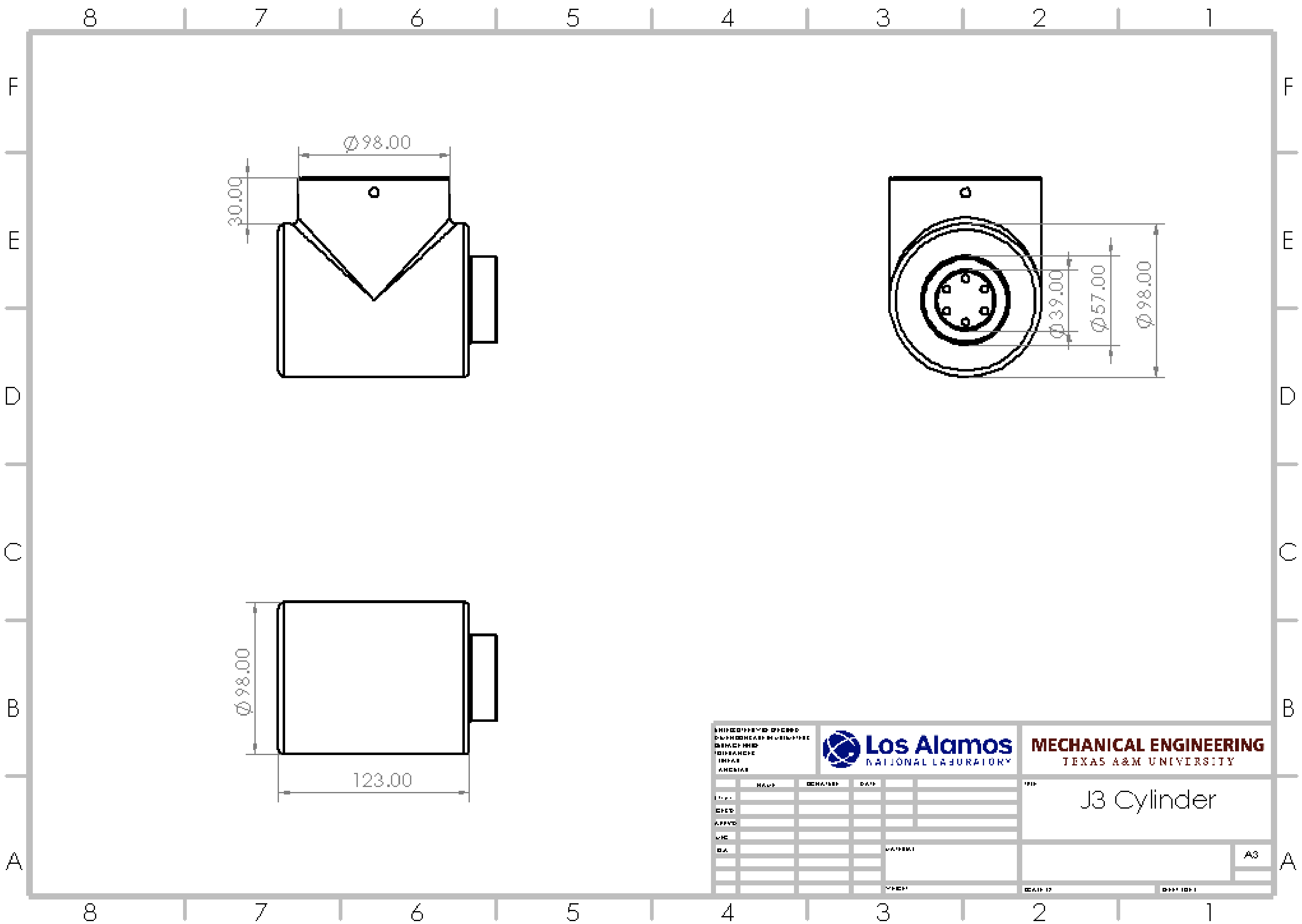


Figure E-16: J3 Cylinder Engineering Drawing

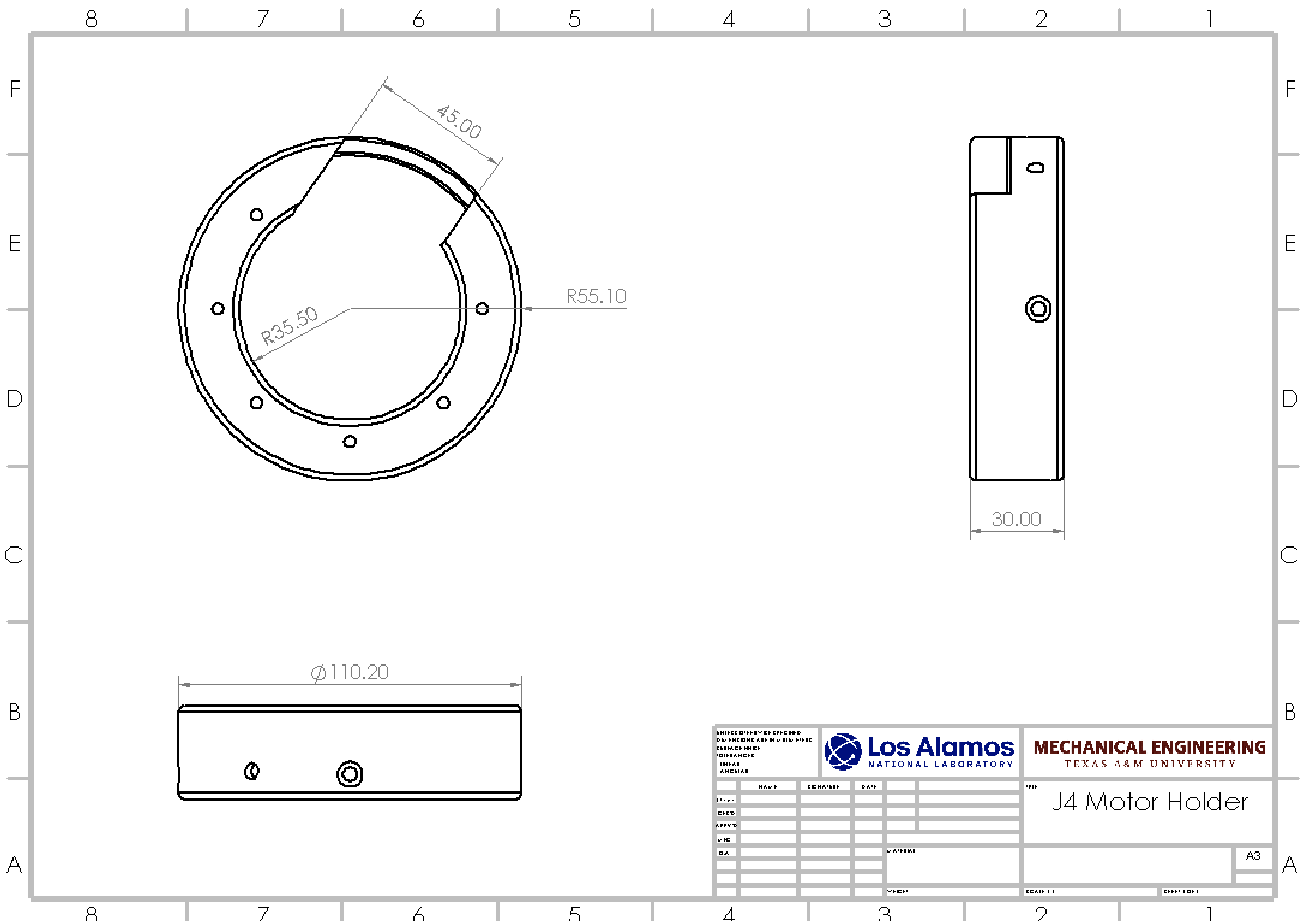


Figure E-17: J4 Motor Holder Engineering Drawing

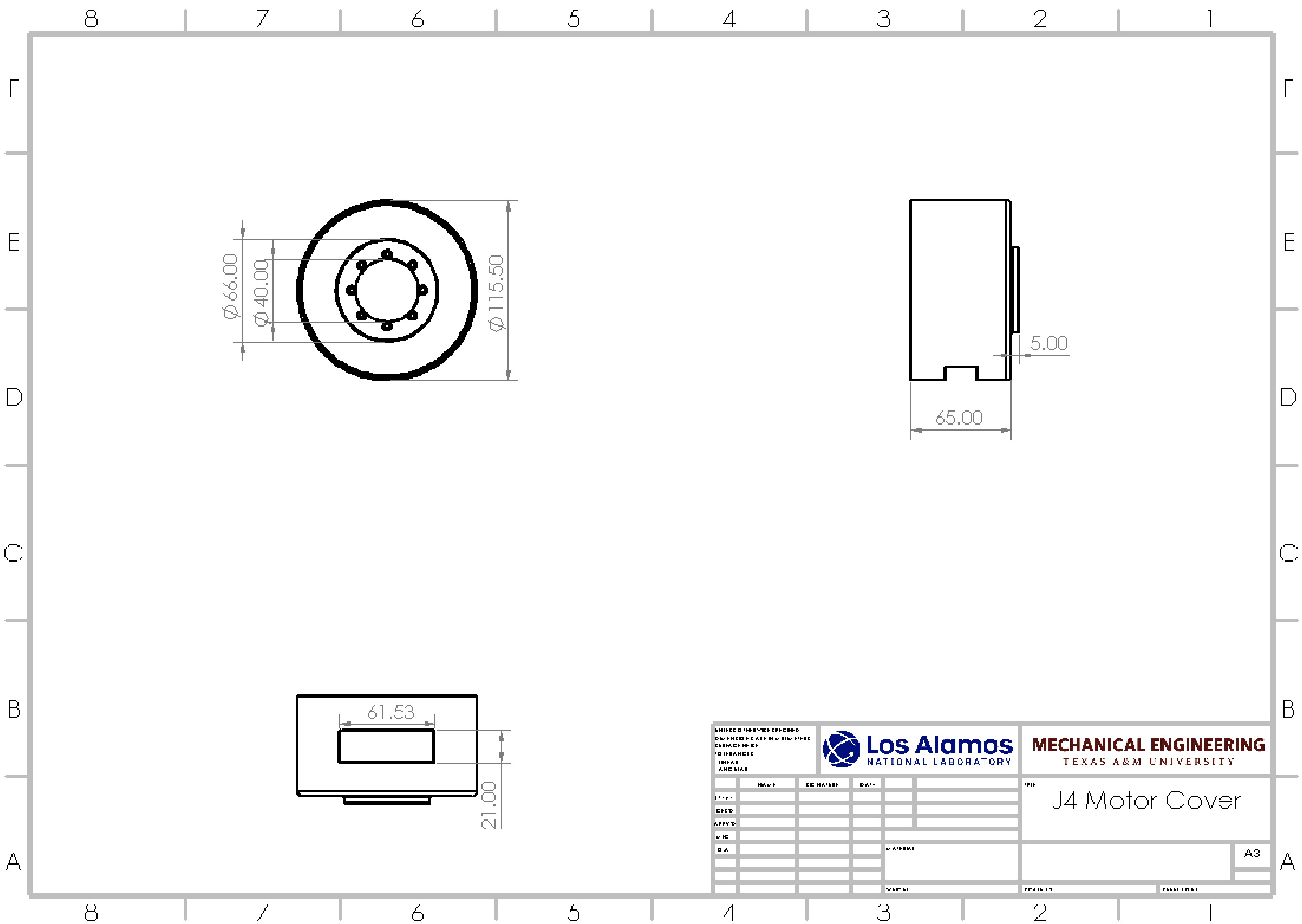


Figure E-18: J4 Motor Cover Engineering Drawing

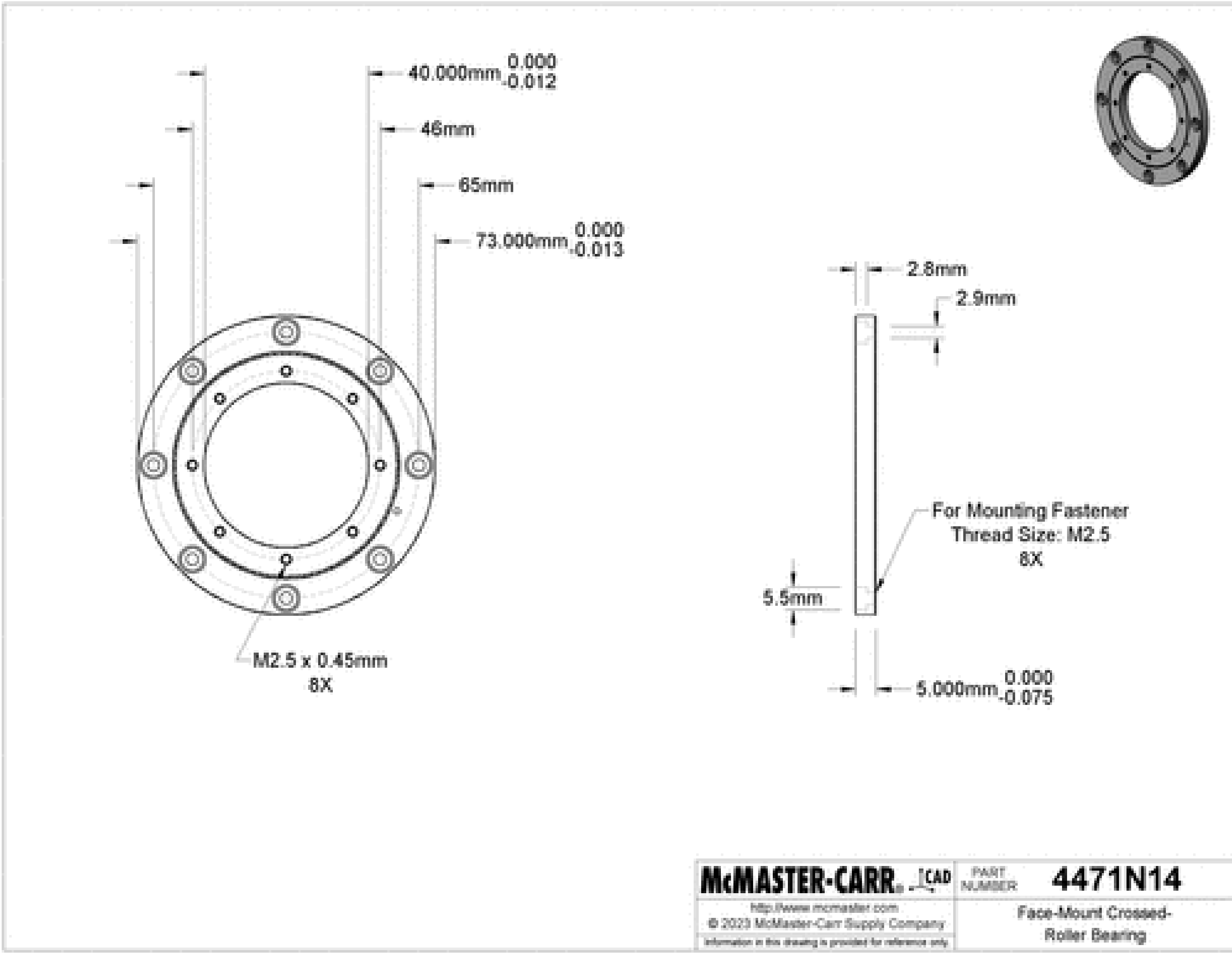


Figure E-19: J4 Cross Roller Bearing Engineering Drawing

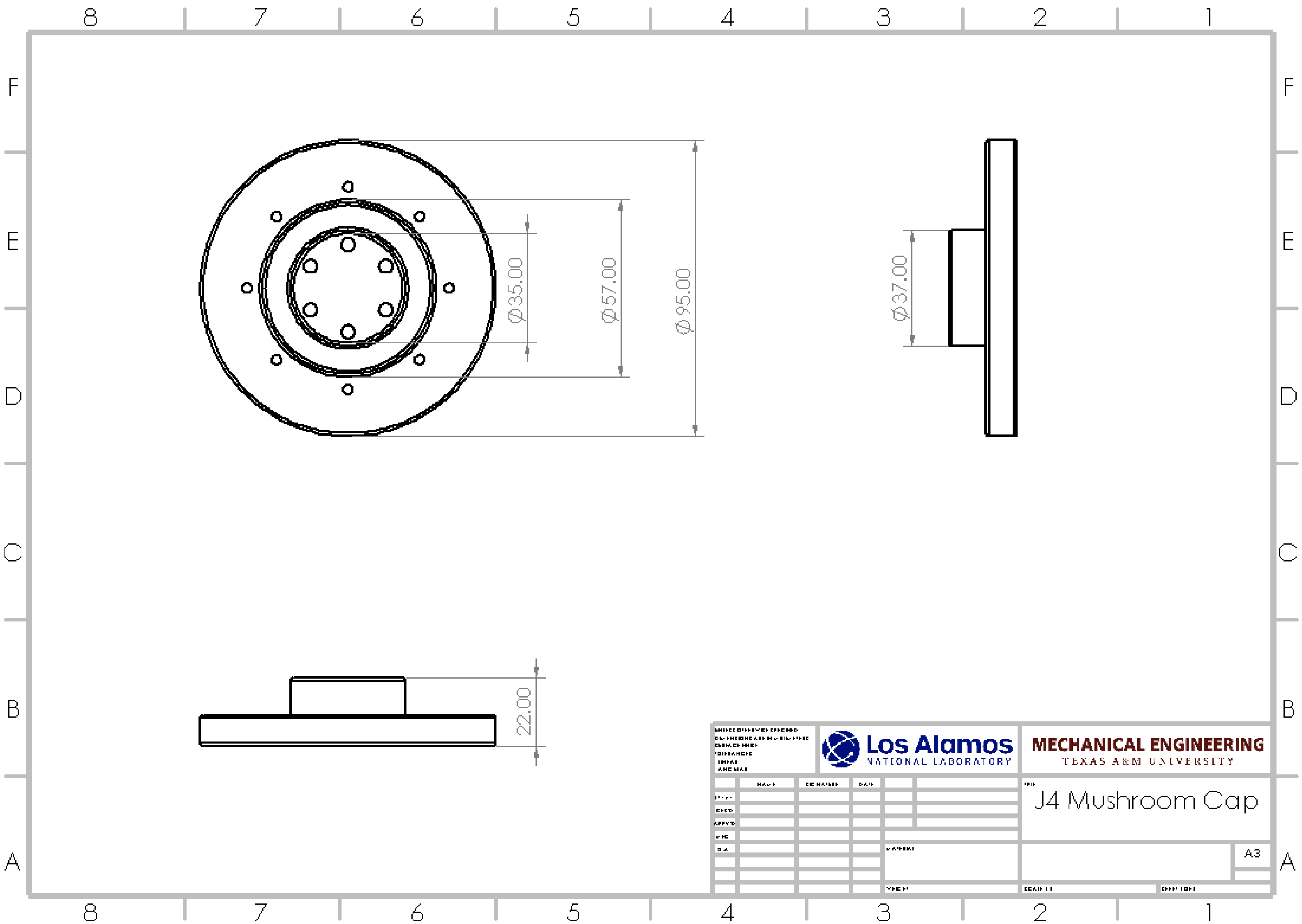


Figure E-20: J4 Mushroom Cap Engineering Drawing

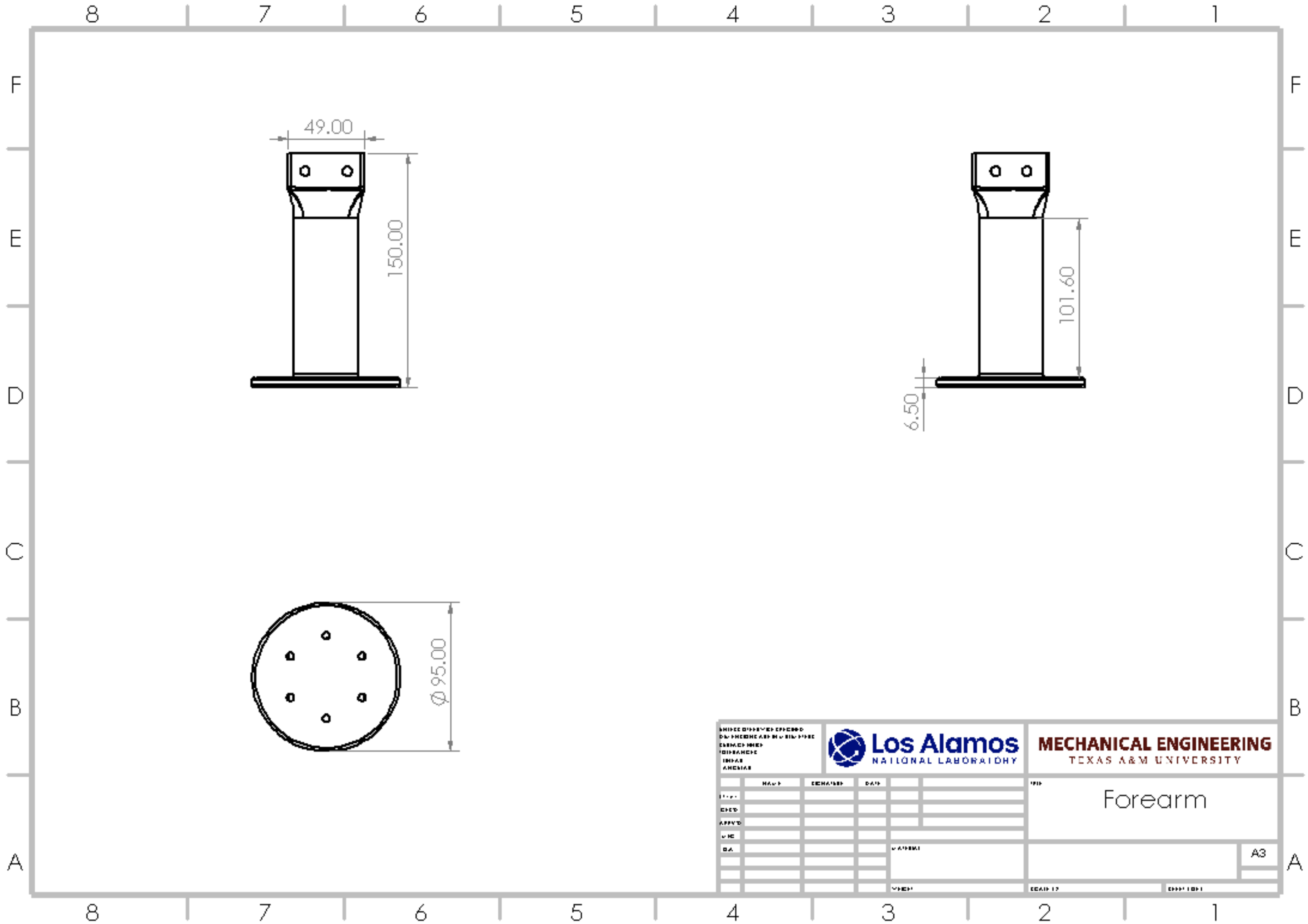


Figure E-21: Forearm Engineering Drawing

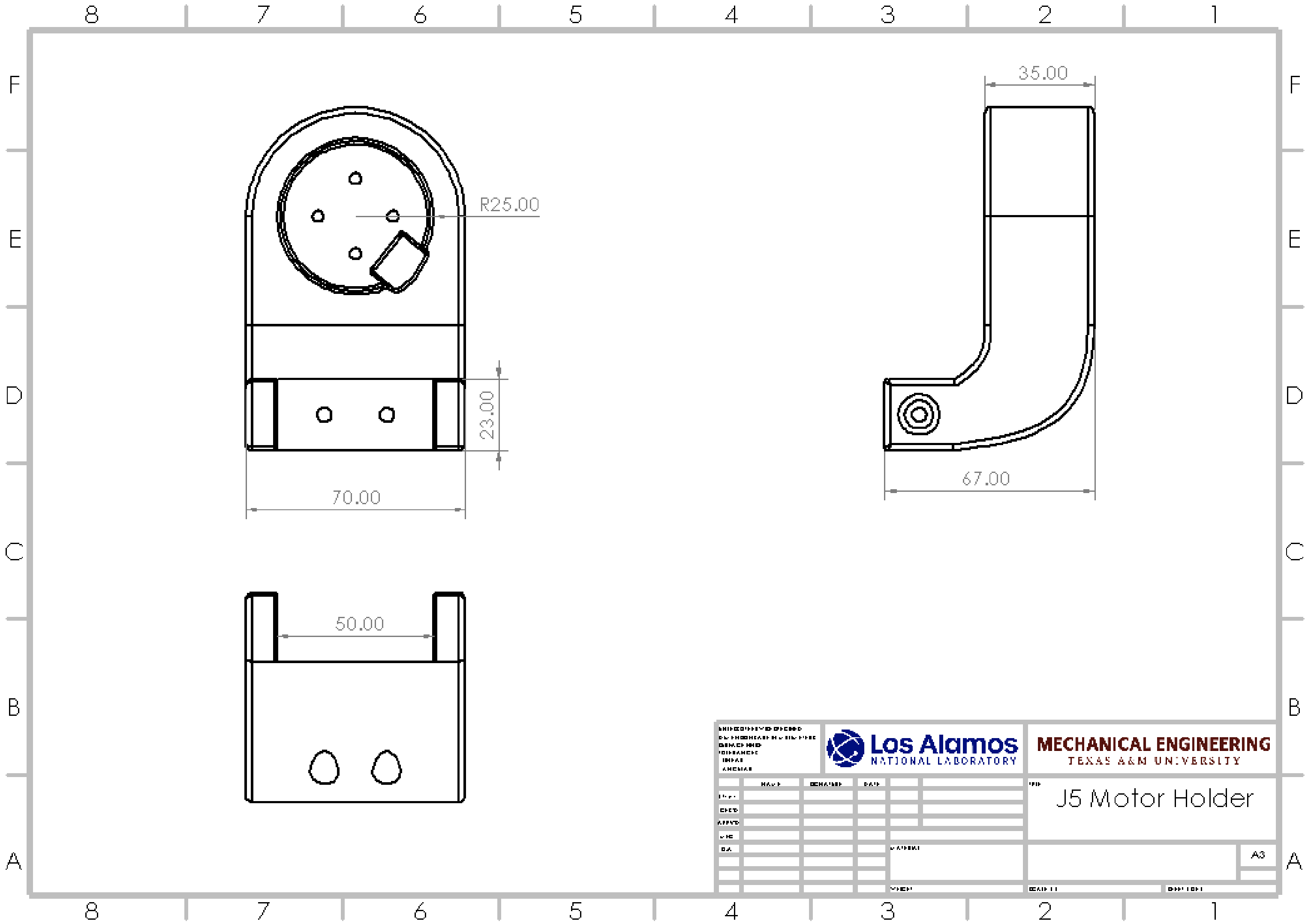


Figure E-22: J5 Motor Holder Engineering Drawing

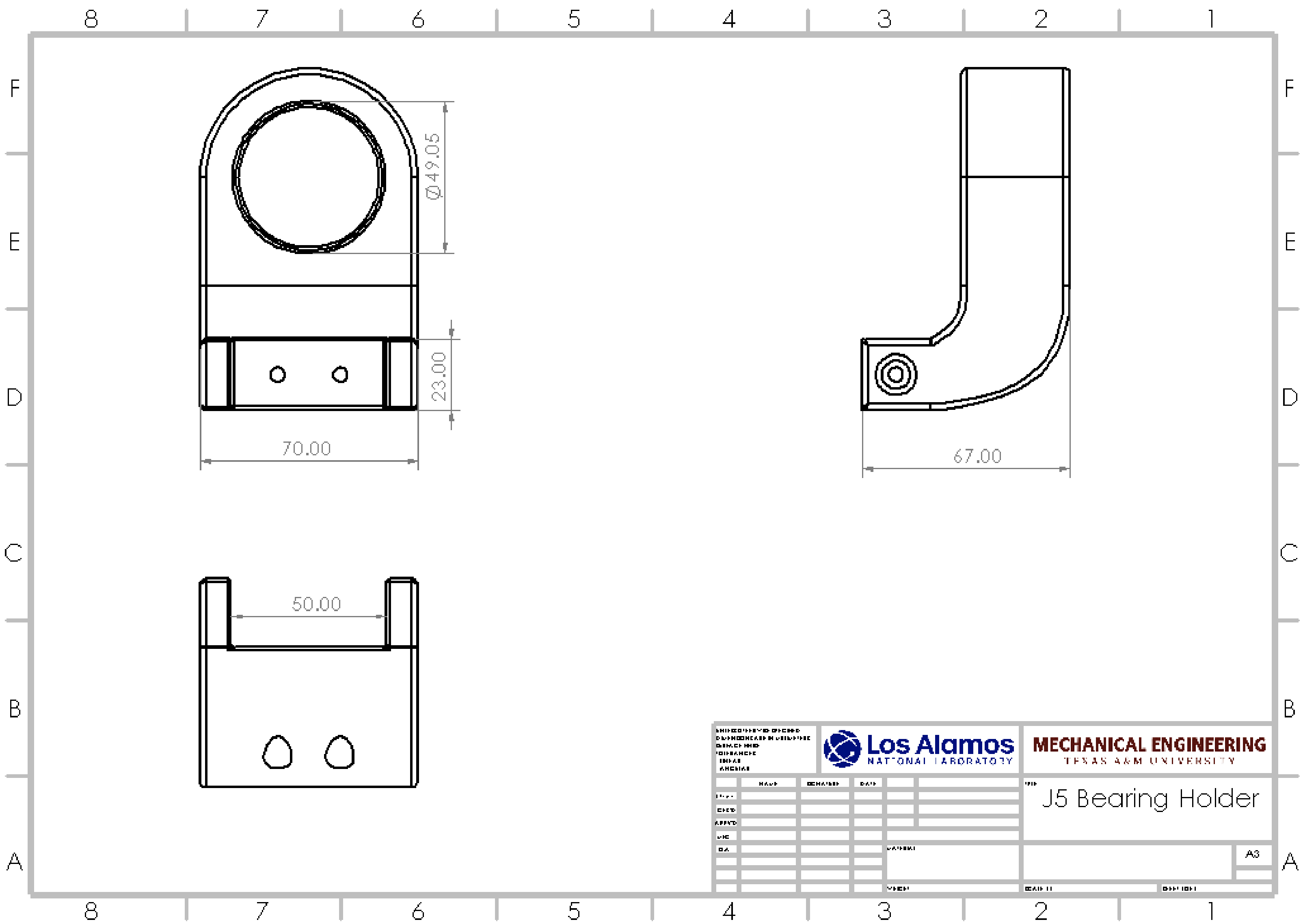


Figure E-23: J5 Bearing Holder Engineering Drawing

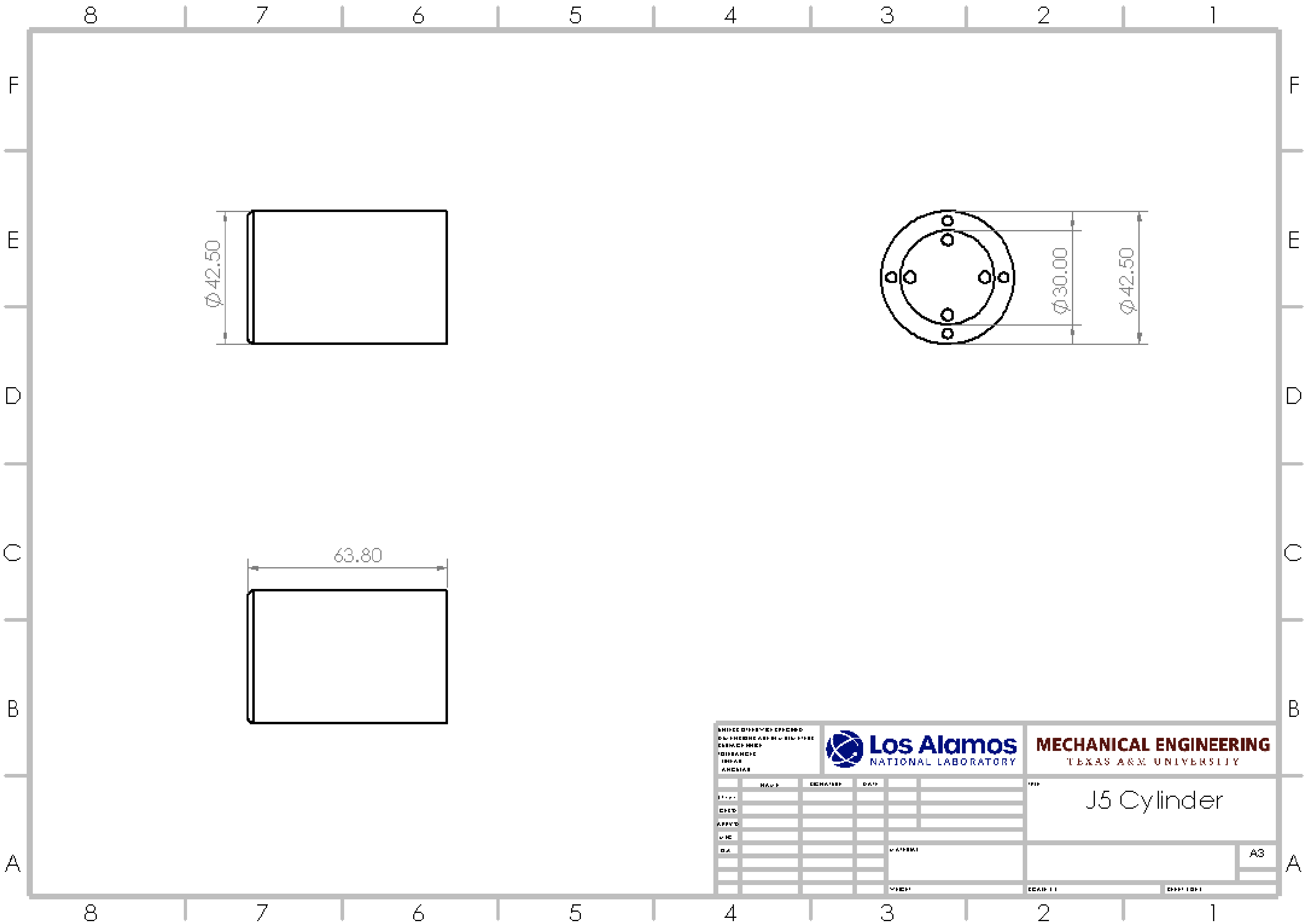


Figure E-24: J5 Cylinder Engineering Drawing

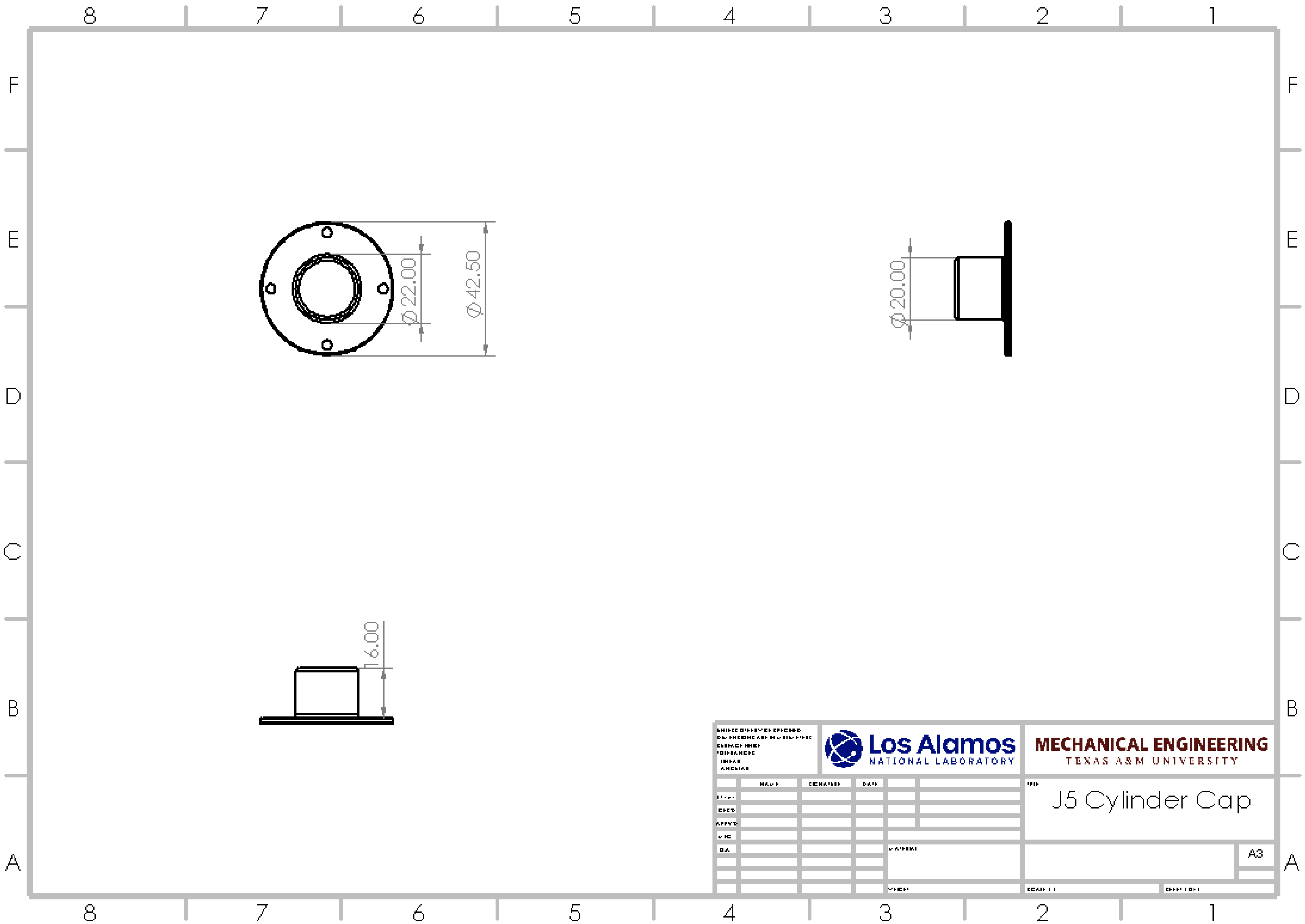


Figure E-25: J5 Cylinder Cap Engineering Drawing

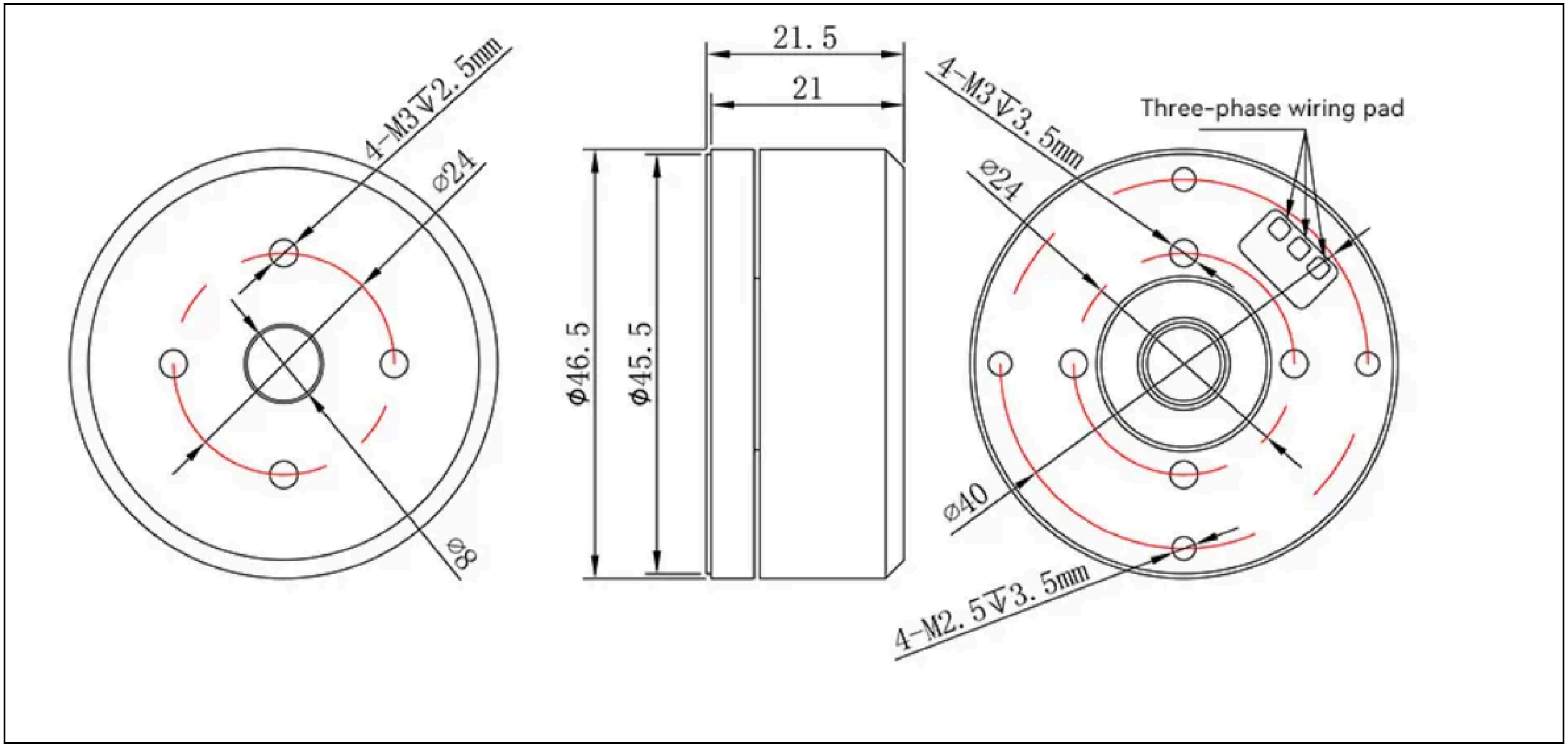


Figure E-26: J5 Motor Engineering Drawing

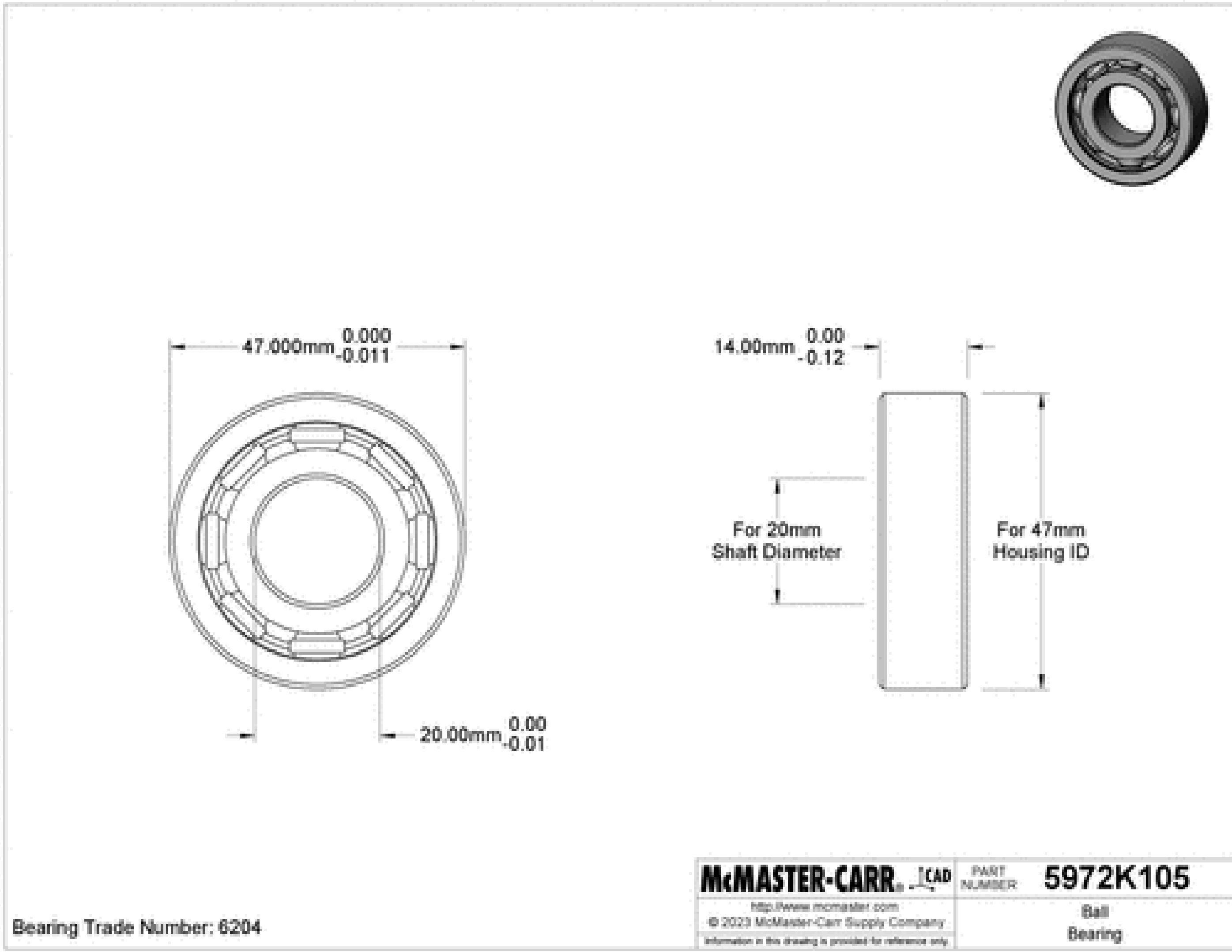


Figure E-27: Ball Bearing Engineering Drawing

Appendix F: Complete Embodiment Checklist

Project Team Name: LANL Human Robotic Arm Capstone						
Team Members: Izzy Baumler, Dalton Boeckmann, Morgan Gullo, Jade Waldron						
Attribute	**Embodiment Design Checklist Item**	**% Complete**	**Status of Design**	**Unresolved Issues**	**Get-well / Recovery plans, and Responsible Person**	**Expected Resolution Date**
Function	Are the customer needs satisfied, as measured by the target values? Is the stipulated product architecture and function(s) fulfilled? What auxiliary or supporting functions are needed?	100%	The team has incorporated 5 motors into the design to account for the 5 degrees of freedom wanted by the customer. To meet the speed requirement very fast brushless DC motors are being utilized to increase the speed of the robotic arm. The speed of one rotation can be measured once joints have been assembled. Supporting functions would be the electricity needed to power the motors as well as the motors being able to operate with the attachement of 3D printed parts.	Issues will occur as assembly begins. The issue of obtaining a power source to supply each motor needs to be resolved	Redesigning the CAD, printing with stronger filament, borrowing power source from TAMU facilities. Entire Team	March 1, 2025
Working Principles and Form solutions	Do the chosen form solutions (architecture and components per function) produce the desired effects and advantages? What disturbing noise factors may be expected? What byproducts may be expected?	100%	The team has finished the full prototype and is in the process of printing parts. Motors are being tested to check working principals. Analysis has been performed on the robot structure to ensure it can hold itself up and work properly. There may be mechanical noise from the brushless DC motors or vibrations created from turning the robot very fast. A byproduct of heat from the motors may be expected.	Figuring out how to get the motors to move simultaneously. Assembling the robot and iterating through parts that have unexpected problems or don't fit properly.	Consulting experts who have experience with these motors. Printing joints with stronger filament if they begin to break under stress. Entire team	March 1, 2025
Layout, Geometry, and Materials	Do the chosen layout, component shapes, materials, and dimensions provide minimal performance variance to noise (robustness), adequate durability (strength), efficient material usage (strength to mass ratio), suitable life (fatigue), permissible deformation (stiffness), adequate force flows (interfaces and stress concentrations), adequate stability, impact resistance, freedom from resonance, unimpeded expansion and heat transfer, and acceptable corrosion and wear with the stipulated service life and loads?	100%	The chosen layout, component shapes, materials and dimensions have provided us with the multiple of the requirements mentioned on the left. At this stage of our robot, it is difficult to quanity some of these metrics. As the robot progresses we will evaluate these metrics and ensure that progress is being made towards them to ensure an efficient robot arm.	We plan on using PET-G instead of PLA for final print but will get final confirmation from our sponsor soon.	We will evaluate if certain metrics are failing and make adjustments if time/money allows. Jade	March 1, 2025
Energy and Kinematics	Do the chosen layout and components provide efficient transfer of energy (efficiency), adequate transient and steady state behavior (dynamics and control across energy domains), and appropriate motion, velocity, and acceleration profiles?	100%	An electrical layout was created to mitigate the need for a very strong battery to power the motors needed for the robot. Brushless DC motors were chose in order to achieve the motion, velocity, and acceleration profiles wanted by the sponsor. Calculations have been conducted on the steady state behavior to ensure the robot can maintain stability at steady state . The weight of the robot and strength of materials were analyzed.	The behavior of the movement of the robot still needs to be addressed. The motion of the robot needs to be evaluated as the robot is assembled.	Moving motors individually to ensure proper movement and acceleration. Reprinting parts with stronger material if steady state is not acheivable with the current design. Izzy & Dalton	March 1, 2025
Safety	Have all of the factors affecting the safety of the user, components, functions, operation, and the environment been taken into account?	100%	The team has ordered a safety cage (dog kennel) per request from our sponsor. This will properly enclose the robotic arm during testing to ensure no one gets injured. We will also implement a kill switch if the robotic arm malfunctions or becomes sentient.	The kill switch has not been factored into the electrical.	Morgan	March 1, 2025
Ergonomics	Have the human.. machine relationships been fully considered? Have unnecessary human stress or injurious factors been predicted and avoided? 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 processes, capability, and suppliers?	100%	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)? Have the necessary quality checks been chosen (type, measurements, and time)?	100%	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)? Can components be combined (minimize part count) without affecting modular architectures and functional independence of the product?	100%	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 solved? Have the required packaging and dunnage been designed?	100%	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

Operation	Have all of the factors influencing the product's operation, such as noise, vibration, and handling, been considered?	100%	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? Have the materials been chosen and clumped to aid recycling? Is the product easily disassembled?	100%	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 checked? What features have been added to the product to aid in maintenance?	100%	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? Will additional operational or subsidiary costs arise?	100%	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? What design modifications might reduce cycle time and improve delivery?	100%	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 G: Complete FMECA

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

Table H-1. Relevant Standards and Codes

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