MEEN 401 INTRO TO MECH ENGR DESIGN; SECTION 902

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DR3 REPORT

TEXAS A&M UNIVERSITY
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Human Robotic Arm

Sponsor: Los Alamos National Laboratory

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

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

Executive Summary

Students from Texas A&M University will design, with the help of Dr. David Mascarenas from Los Alamos National Laboratory, a robotic arm attachment for solving a crucial cleaning need within nuclear waste facilities. This project aims to enhance remote hazardous material handling operations by affixing a 6 DoF robotic arm to the body of a quadruped Boston Dynamics Spot robot. These robotic arms attached to Spot robots will be built and designed to clean radioactive waste residues to minimize contamination risks without direct human intervention.

The project arose from accessibility limitations and safety problems common in nuclear waste facilities identified during discussions with professionals at the Los Alamos Research Laboratory. So far, the team has done the research, established the requirements of the project, and elaborated on the initial ideas in a period of 10 weeks, during which they had to be certain that their solution would be efficient, lightweight, and capable of removing the waste in a hazardous environment. This robot will receive inputs from a computer, with a primary focus on achieving a functional frequency of at least 1 Hz to ensure reliable performance under various conditions.

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

Table E1: Customer Needs Table

#	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

These needs were also translated into design specifications using the House of Quality, or HOQ, integrating customer feedback, online research, and technical standards. It showed how different design parameters, like weight, torque, and maneuverability, are all interconnected. Using the HOQ also pointed out an important trade-off among some factors: for example, optimizing torque does not affect the weight of the arm. Moreover, the group identified the key metrics for maximum torque output of 2-10 Nm, positional accuracy of 10-30 mm, and movement speed of 1 m/s to satisfy the customer needs. These specifications were verified by cross-referencing the functional requirements with the customer needs and prioritizing the design targets, as shown in **Table E2**. These extensive processes and specifications set the basis for developing a robotic arm to perform dynamic tasks in specific conditions.

Table E2: Customer Needs and Functional Requirements Cross Reference

Requirement #	Need #	Metric	Importance Score (1 to 5, 5 = most important)	Required Values	Units
1	7,5	Weight of the Arm	3	<14	kg
2	1,2,4	Maximum Torque Output	3	2-10	Nm
3	2,3,8	Positional Accuracy	3	10-30	mm
4	2,5	Reach of Robotic Arm	3	>0.67	m
5	3,5,7	System Mass Distribution	2	0.209	kg/cm
6	1,2	Movement Speed of the Arm	5	1	m/s
7	1,2,3,5	Frequency of Motion	5	1	Hz

Once the team identified the needs from both a functional and customer standpoint, the team needed to brainstorm concepts that could potentially meet these needs and become a solution. The team brainstormed possible solutions using a variety of idea-generation techniques. Such techniques included brainstorming, TRIZ- theory of inventive problem solving, and design by analogy. These techniques enabled the team to consider a wide range of ideas. The brainstorming sessions generated many ideas, including the use of energy harvesting and voice recognition for control. TRIZ helped solve major contradictions, such as weight reduction with no loss of movement speed, by using either electromagnets or flexible materials for effective motion. Design by analogy drew inspiration from mechanics in the human arm and elephant trunk, enhancing the flexibility and precision of the design in possible robotic arm solutions.

From these creative exercises, four different concepts were developed by the team as seen in **Figures E1 - E4.** In each of these concepts, different ways of addressing the project's core requirements were provided, enabling the team to evaluate various ways to optimize performance.

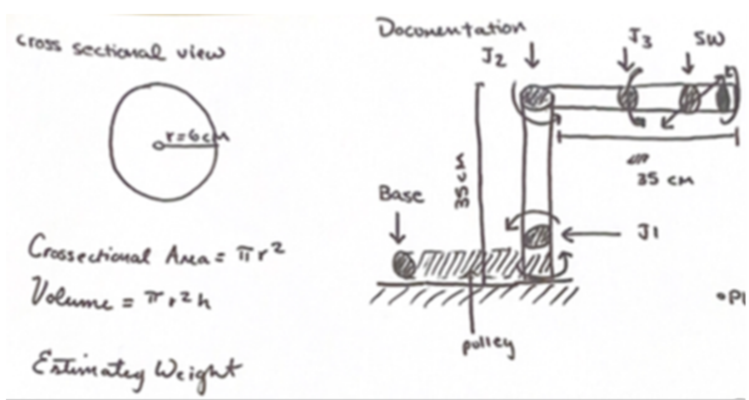

Figure E1: Concept 1

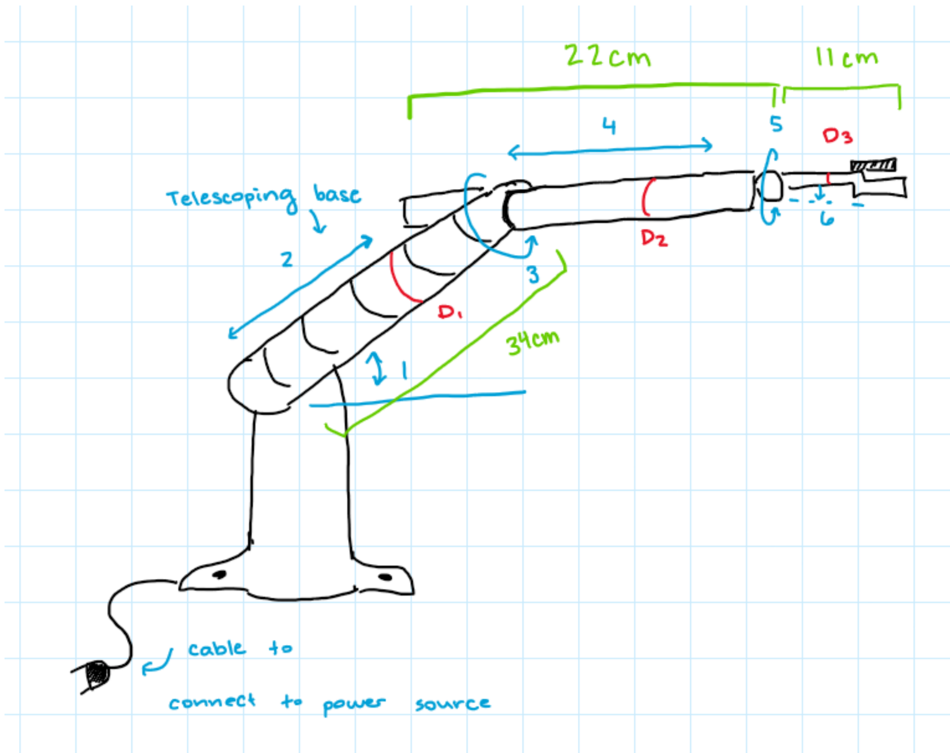

Figure E2: Concept 2

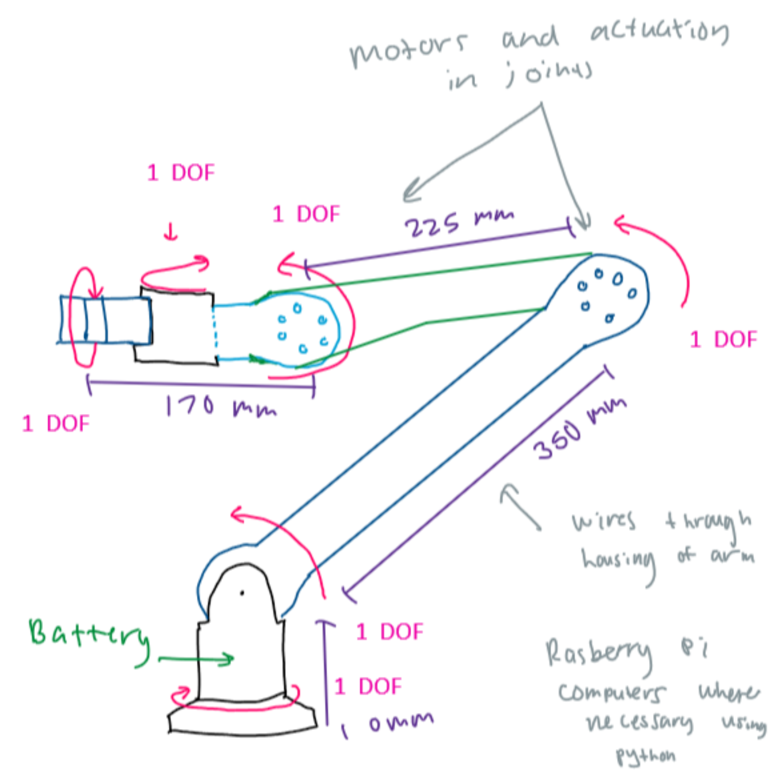

Figure E3: Concept 3

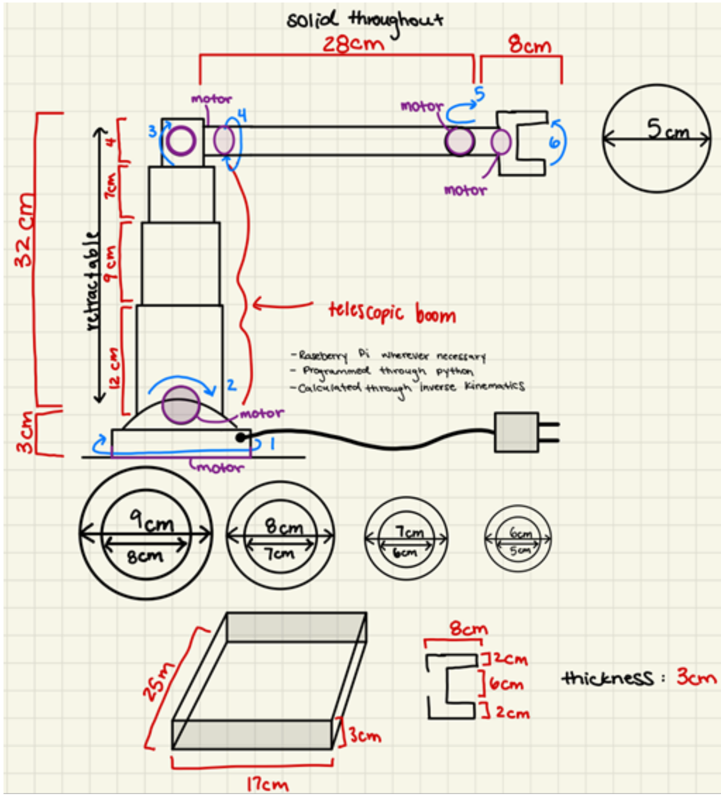

Figure E4: Concept 4

The team used a morphological analysis matrix to refine these ideas by organization and combination using sub-functions such as movement and energy conversion. The matrix allowed this team to then effectively prioritize the solutions and develop four viable design options, balancing functionality with efficiency and innovation, for the next steps in development. In the selection of the final design for the Human Robotic Arm, the team made use of two important tools: the Pugh chart and the Quantitatively Driven Team Effort Selection Matrix (QDTESM). First, the Pugh chart compared four concepts against a baseline design in terms of customer needs like maneuverability, precision, stability, and weight. Concept 4 achieved the highest score and emerged as the leading design, offering a lightweight, stable structure that closely aligns with the intended needs. The team identified that Concepts 1 and 2 ranked at lower points against every criterion.

The QDTESM gave a more detailed quantitative comparison of the concepts based on functional requirements for arm weight, torque output, positional accuracy, and movement speed. Once again, Concept 4 ranked the highest, distinguished by its lightweight design and high-frequency motion, making it the strongest candidate. In contrast, Concept 3, despite having a design similar to existing models, ranked the lowest due to its heavy weight and poor performance. Ultimately, Concept 4 was chosen as the final design based on its superior scores in both the Pugh chart and the QDTESM. It was noted for its overall performance, best meeting customer and functional requirements than the other concepts. Once Concept 4 was selected, the team focused on structuring the design into functional modules to simplify and streamline the development process.

Key modules were identified in the product architecture, each responsible for specific functions that enable the robotic arm's capabilities as seen in **Figure E5**.

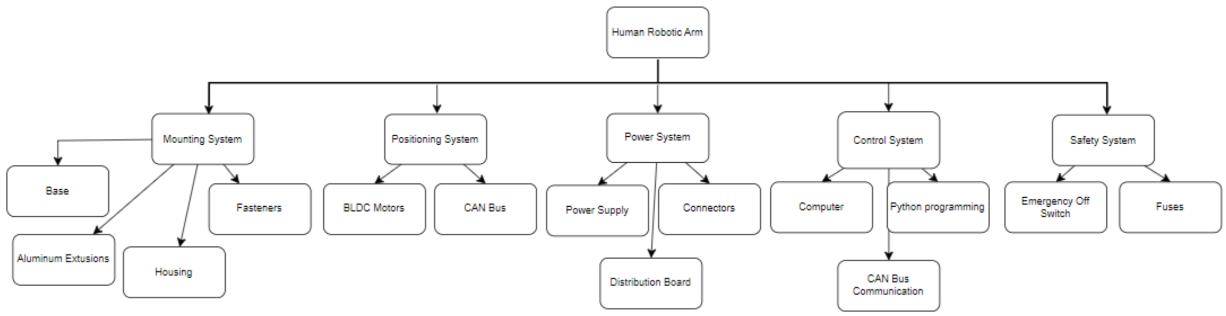

Figure E5: Product Architecture

The mounting system serves as the base for stability and support of the arm during operation. The positioning system integrates brushless DC motors with encoders for precision in multiple DoFs of the arm. The power system provides flexible adjustable power to the arm, while the control system processes inputs and sends commands to the motors through a central processor. A safety system with an emergency stop and motor fuses ensures user protection and operational safety.

These modules function in a very efficient manner while maintaining modularity, allowing for ease of upgrades and making the system more adaptable for the future. A geometric diagram was developed for the interactions among modules. This diagram shows relationships in material flow, energy transmission, and information signaling.

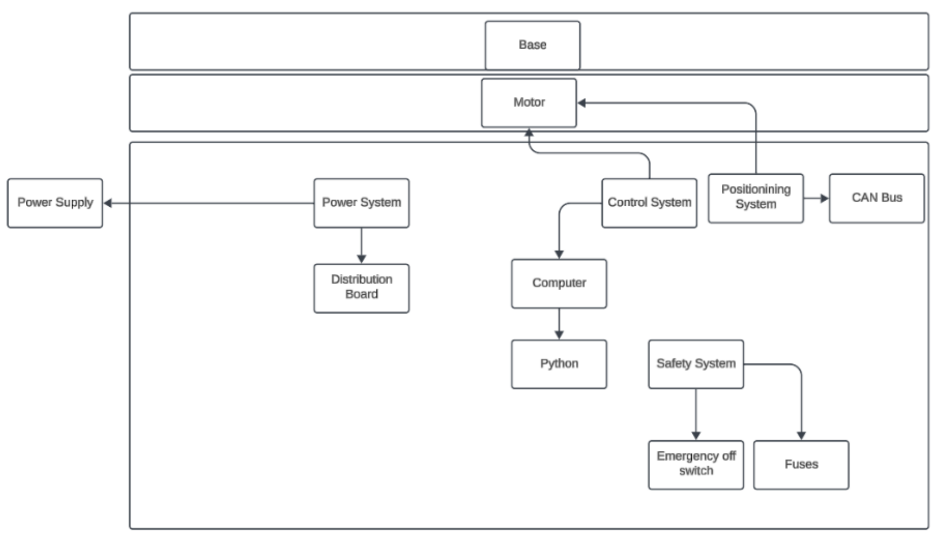

Figure E6: Product Architecture Geometric Diagram

From this, a detailed CAD model was also developed to visualize the mechanical design, featuring the base, aluminum extrusions, joints, and DOF for the movement of the robotic arm as seen in **Figure E7**. The embodiment design ensures that the robotic arm is efficient, flexible, and easily adaptable for future improvements, meeting the required functional and safety requirements.

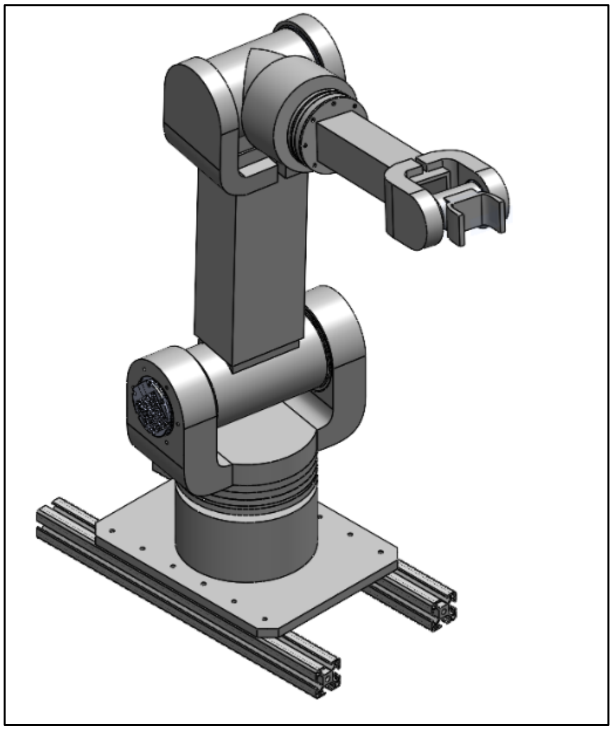

Figure E7: Detailed SolidWorks Assembly of Final Design

Throughout the design process, the team needed to validate this design to ensure that the robotic arm wouldn't break under various conditions. In doing this the team performed calculations to justify design parameters and components. Verification of system performance, safety, and reliability in a variety of environmental and other operational conditions was required to validate the system's design.

The team wanted to validate that the arm could carry itself without compromising any of the performance of its motors. This validation was done focusing on maximum torque conditions for the arm, specifically when joints J2 and J3 are fully extended. The team calculated the weight of each component and the torque experienced by the motors at these critical positions. These calculations ensured that the motors of the arm would not be over-torqued or over-stressed during operation. The validation proved that even at full extension, the arm would remain stable, and the motors would be within their torque limits, hence ensuring safety in real-world scenarios.

The second step in validation was to test the materials used in the construction of the arm, especially PLA- Polylactic Acid, used for 3D-printed components. The tensile strength and flexibility of the material were investigated by the team with ASTM-compliant tensile and flexural tests, respectively. This showed that, printed at an infill density of 40%, the PLA would possess tensile strengths (11.43 MPa) and flexibility (elastic modulus 1367 MPa) appropriate to the task required from the robotic arm at work. These tests ensured that the 3D-printed components would not fail under typical use, providing reliability and durability for the arm's long-term performance.

Further verification of the integrity of the design was done by the team through the use of Finite Element Analysis with SolidWorks. This analysis was a simulation of how the arm would respond to real-world forces and stresses, and was used to help validate our experimental test on the PLA. The FEA results were consistent with the experimental data, showing that our FEA simulation would be reliable when performing further analysis on various components of the arm. Through simulation, it could also be shown that when these typical operating forces were applied to the arm, there was no plastic deformation or failure;

thus, validating a strong and reliable design. These validations ensured that the arm would handle the required loads but also provided confidence in the material and structural integrity of the design, laying a solid foundation for the continued development of the system.

The project budget is a $5,000 grant provided by Los Alamos National Laboratories and the J. Mike Walker '66 Department of Mechanical Engineering within the Texas A&M University College of Engineering. This budget will not be exceeded so long that the team follows the defined Bill of Materials, so parts won't need to be replaced. Moving into the plan for MEEN 402, which will entail the fabrication and validation of the team's prototype. The team has outlined a definitive validation plan that will carry into MEEN 402 and end in March 2025. The validation plan for the robotic arm prototype is designed to ensure that the system meets the predefined requirements for functionality, structural integrity, and overall performance. The validation process will be broken down into key sub-validations that focus on specific sub-systems such as structural integrity, motor performance, joint functionality, and multi-motor integration. This is done so that through systematic validation, the robotic arm will work as expected in realistic conditions and perform reliably for a range of operational scenarios.

The main objective of the Validation Plan is to verify that the robotic arm acts correctly in all its DoFs. It will start by validating one motor and its associated DOF. If the motor behaves well, other motors and their corresponding DoFs will be progressively implemented in the system. Each validation step will be evaluated by using a simple "yes" or "no" decision to determine if the solution meets or does not meet the predefined performance criteria. The team will perform a structural validation that will aim at ascertaining that the structure of the arm is strong enough to bear the operational loads without collapsing or deforming. For this, the team will carry out FEA simulations to study the stresses and strains that the critical components of the arm, such as linkages, J1 base, and end-effector, will be subjected to under various loading conditions. The FEA will give quantitative results to lead the selection of materials for the optimization of the design concerning strength and durability. This will be followed by physical testing, which will validate that the actual performance of the arm is true as theoretically deduced and thus its structure is sound.

Motor validation will be done to ensure that each motor correctly responds to input commands and provides the correct output motions. Initial testing will involve small translational and rotational movements to verify that the motor aligns with the corresponding joint movements. The last stage of the validation process will be multi-motor system integration. It will involve the testing of simple coordinated movements using two motors and expanding to more complex motions involving all motors working together. This is to ensure that all motors synchronize correctly, with no interference or delays between components. Any issues related to motor calibration, response time, or interference will be addressed in this stage to ensure smooth and synchronized operation. Testing will be carried out at especially allocated places that guarantee a controlled environment for carrying out the right experiments. In addition, such testing tools are indispensable for validating functionalities of a design and reliable arm behavior in a variation of conditions.

The team will also collaborate with the sponsor in ensuring test plans and procedures are suitable and appropriate for the needs of the project. Regular reviews of the test plans will be carried out during this phase to ensure there are no delays in the projects. From this, each sub-system will be systematically validated by the team to meet all functional and structural requirements of the prototype of the robotic arm. Successive phases of the validation plan will lead to a fully integrated, reliable robotic arm capable of handling expected loads while accomplishing complex tasks with great precision.

By May 2024, the team will deliver the primary outcome for MEEN 402: a fully functional prototype that has been validated through comprehensive mechanical testing. The final deliverable will also include a document that summarizes all the work completed throughout the course, serving as a valuable resource for future teams to continue improving upon the design.

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Glossary Table

Term	Definition
ABB	ASEA Brown Boveri
CAD	Computer-Aided Design
DOE	Department of Energy
DoF	Degrees of Freedom
HOQ	House of Quality
LANL	Los Alamos National Laboratory
QDTESM	Qualitatively Driven Team Effort Selection Matrix
SNPS	Solution Neutral Problem Statement
SRNL	Savannah River National Laboratory
TDD	Task Dependency Diagram
TRIZ	Theory of Inventive Problem Solving
WBS	Work Breakdown Structure

1. Introduction

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 condition. 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 develop 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 6-DoF robotic arm attachment for a quadruped robot to assist with cleaning operations inside nuclear waste tanks.

1.1. Problem Identification

The design team in collaboration with engineers from 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 6 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.

1.2. Current Problem Statement

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.

In response, the project team proposes a 6-degree-of-freedom robotic arm mounted on a quadruped robot. The quadruped robot provides stability on uneven surfaces, while the 6-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.

1.3. Report Overview

The preliminary research for this background will provide an overview of a range of 6-degree-of-freedom robotic manipulators, their designs, and functionality. The Problem section defines how the team has limited the scope of the project, set major objectives, and identified stakeholders involved notably LANL. Next is the Customer Needs section, which introduces the thorough design analysis process. The Design Requirements and House of Quality sections outline the functional requirements the team has chosen to measure LANL's performance, along with linking the metrics to customer needs and setting target values. The section Functional Modeling explains what each subsystem of the robotic system will be required to do. The idea generation section explains how solutions for the subfunctions of the robotic system were developed.

The next section of the report describes how these ideas were put into concepts and explains the operating principles involved in each of those concepts. Finally, the concept selection portion discusses the evaluation tools that were implemented to assess each concept and also describes the reasoning behind the final selection. The Project Management section outlines a timeline of the remaining design activities of MEEN 401 in anticipation of the start of MEEN 402. The Final Deliverables section represents what is expected when the course MEEN 402 closes. The Future Work section outlines the plans by the team to complete design activities highlighted in the Project Management section. The section on External Collaborations briefly describes some of the design challenges faced and how partnerships were developed to secure supplemental funding, components, and technical expertise. Finally, the Conclusions section summarizes the present status of the LANL project.

2. Background Research

2.1 Types of Industrial 6 DoF Robotic Arms

Within Industrial settings, three very common types of 6 DoF robotic arms are used for various manufacturing needs. These robotic arms include the articulated robot, the Cobalt Collaborative Robot, and the delta robot. All of these robots and their specific mechanical designs offer different mechanical behaviors that present both advantages and disadvantages.

Articulated robots are designed with successive rotary joints or prismatic, often in a configuration resembling a human arm, with joints providing pitch, yaw, and roll movements [1]. Each joint contributes one degree of freedom to this robot, and therefore it can move around in space with quite high flexibility about six axes. For example, robots from the KUKA KR series are known to use powerful motors at every joint. This allows them to have precise control over complex movements; hence they find applications in welding, material handling, and assembly [2]. Due to this configuration in the series, they are heavy and bulky; therefore, they cannot work in tight spaces, such as nuclear waste tanks. Force-torque sensors are primarily used in articulated robots for tasks involving delicate objects. However, they can increase complexity and require extensive tuning for specialized operations

The Cobot Robot, in contrast to traditional articulated robots, has lightweight frames integrated with Series Elastic Actuators for better compliance and smooth motion [4]. These actuators contain elastic elements such as springs that can absorb shocks. Therefore, these robots are much safer to work with in human-robot collaboration. Sensors and vision technology are also integrated into robots to detect obstacles and reduce the risks of collision in dynamic environments. The result is that this modular mechanical design enables them to be easily reprogrammed, thus easily adapting to the evolution of tasks. However, cobots generally have lower payloads and slower speeds compared to their traditional industrial counterparts, which limits their application in light-duty applications like inspections and packaging but not heavy hazardous waste removals.[5] This is due to the inherent limitation imposed by the necessity for lighter motors and reduced structural rigidity in favor of safety, due to close collaboration with humans.

Delta robots have a parallel configuration of three or more lightweight arms linked to a common lightweight base, which offers them low inertia for fast and precise movements [6]. These high-speed applications enable them to be used in sorting and packaging small items in industries like pharmaceuticals and food. However, due to the limited degrees of freedom, in light of the mechanical structure usually meant for movement along the X, Y, and Z axes, it is quite challenging for a delta robot to perform tasks that may involve moving heavy or irregular objects easily [7]. This is because the design focuses more on the question of speed than on payload capacity, where lighter arms and motors bring them down in their ability to perform tough tasks, such as hazardous waste management.

2.2 Previous Technologies and their Advantages and Disadvantages for our Applications

While articulated robots, cobots, and Delta robots have certain advantages, there are a considerable number of problems when applying these to hazardous waste management. Articulated robots, such as those in the KUKA KR series, can have great flexibility in complex movements but possess large physical dimensions with considerable weight, which affects their appropriateness for use in confined areas like nuclear waste tanks [1][2]. Their dependency on exacting force control makes them complex with the need for highly sensitive sensors to avoid damaging fragile material, possibly delaying operations. Safety and human collaboration have been the primary factors of robot design, as well as the Universal Robots UR5. However, it faces payload capacity and operational speed challenges. Thus, there are opportunities to improve efficiency regarding heavier waste materials at faster operational speeds.

The Delta robots, such as the ABB FlexPicker, offer high-speed, high-precision manipulation; however, they have generally limited payload capacity and range of motion. Because of this, they are unsuitable for application in a hazardous environment with non-standard shapes of waste [6] [7]. These design limitations put into perspective the requirement for a robotic arm that can come up with a middle ground between compact size, operating speed, and flexibility. The ideal solution would have to improve upon the strengths of these robotic types as well as make unique modifications that will make them carry out hazardous waste management operations efficiently.

2.3 Engineering Concepts Relative to Robotic Design

The design of robotic arms meant for hazardous waste management involves several critical engineering concepts, which speak to the unique nature of challenges posed by this environment and its tasks. These include kinematics, materials selection, control systems, and safety measures.

Understanding kinematics is necessary for manipulation in confined spaces and is a key aspect of the design of robotic arms. In hazardous waste environments, a robotic arm must be highly dexterous and able to avoid obstacles. To model the motion of such an arm and to perform reachability and workspace calculations, the Denavit Hartenburg convention is widely used [26]. For the accuracy needed to handle waste of various shapes and sizes with precision and stability during service, the robotic arm requires a deep understanding of both forward and inverse kinematics [26][27].

Selection of materials is another important issue. Robotic arms for hazardous waste management should be made from materials that provide adequate strength and rigidity while being resistant to corrosion caused by harmful substances. For ease of mobility, lightweight yet strong materials, such as titanium alloys or special polymers, may be favored in order to reduce the overall weight of the arm for this device to work well in places where there is not much room for motion [31].

In this respect, control systems are critical to perform robotic arms effectively in hazardous environments. Advanced control algorithms, like adaptive control and model predictive control, will enable the arm to respond against changing loads and conditions with smooth and precise motion [32]. Integrating learning techniques will further enable a robotic arm to learn new tasks or unexpected environmental changes for higher efficiency and effectiveness in hazardous waste management processes [33].

Robotic systems must be designed with safety features, as they may operate in environments with humans. In this sense, the use of force-torque sensors enables the control of the interaction between the robotic arm and the environment for safe operation, even in dynamic conditions [33]. Moreover, emergency stop systems and safety enclosures will provide protection for human workers against dangers that may result as a consequence of the movements of the robotic arm [34].

Overall, engineering design concepts in robotics should focus on making a robotic arm flexible, strong, and safe. Advanced kinematics, combined with sophistication in control systems and materials selection, together with sufficient safety measures, can provide an optimum approach to the development of a robotic arm that is effective at performing specific hazardous waste management conditions.

3. Problem

3.1. 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 6 DOF and can move through its full range of motion in each degree of freedom around 1 Hz.
Customers	Department of Energy, National Research Laboratories

3.2. Mission Statement

Through the development of the SNPS, the team arrived at a mission statement that helps clarify the LANL project team's design goal to meet the needs of the customers. The mission statement can be seen clearly defined in **Table 2**. The mission statement outlines that the LANL project team will design and prototype a 6 DoF robotic arm that is optimized through the design selection of material, robotic actuation for arm movement and control, and the semi-autonomous control system. Considering limited resources and timelines, the team has decided to focus on the design of the mechanical aspects of the robotic arm, focusing specifically on optimizing the speed and dynamic capabilities of the manipulator.

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

Mission Statement: LANL Power Tool Arm Attachment for a Quadruped Spot Robot	
Product Description	Design a 6 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

3.3. Technical Questioning Results

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.

4. Customer Needs

4.1. Customer Needs Table

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 6-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. The team will factor this valuable feedback into our concepts and designs.

4.2. Needs Analysis

A successful 6 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.

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 6 DoF and can move through its full range of motion in each degree of freedom around 1 Hz.

5. Design Requirements and House of Quality

5.1 Identification of Design Requirements

The team used various methods to identify design requirements, target values, and the relative importance of these specifications for our arm. One major tool was customer feedback, which was expressed in interviews and the supplemental design survey. Additionally, online research further confirms target values. These specifications include the weight of the arm which must be less than 14 kg per the payload requirements for the Boston Dynamics Spot Robot [7]. Additionally, the team found that the Maximum Torque Output should be calculated and compared to other arms on the market. The group found that medium-sized arms performing normal tasks should have a torque output range from 2-10 Nm [8]. Also, the positional accuracy of the arm should be around 10-30 mm [9]. Based on the data from the average length of a male human arm, the average minimum length of our robotic arm will be greater than 0.67 m [10]. The movement speed and frequency of motion for the arm will be 1 m/s and around 1 Hz respectively. These two values were recommended by our sponsor to ensure agile movement.

The group also used the Requirements Checklist as a final resource to ensure that requirements were specified for all the main functions of the Human arm design. This checklist ensured that the team specified metrics related to geometry, kinematics, and forces, aligning with the project's scope, which focused on developing a proof of concept rather than a commercial product. Consequently, metrics related to production, quality control, assembly, transportation, maintenance, costs, and schedules, were not included.

If the product is commercialized, the design of our robotic arm must adhere to several key regulations and standards to ensure safety and compliance as outlined in **Appendix D.** According to the Federal Hazardous Materials Transportation Law, regulations must be followed for the safe transportation of hazardous materials, which could apply during the robotic arm's deployment in sensitive environments [15]. The Environmental Protection Agency stipulates that disposal systems for radioactive waste need to be designed with long-term safety in mind [16]. Also, compliance with the Federal Land Disposal Requirements and the Washington State Dangerous Waste Regulations is essential for any waste generated during the arm's operation [17,18]. Additionally, the IAEA-TECDOC-672 highlights the need for appropriate robotic system applications in various operational modes [19]. Lastly, ISO 10218 outlines safety requirements for industrial robots, ensuring that our design prioritizes user safety and operational integrity[20]. By adhering to these codes and standards in **Table D-1**, the team can ensure the reliability of our robotic arm design while meeting the necessary regulatory requirements.

5.2 House of Quality

A House of Quality (HOQ) was constructed to synthesize a coherent set of requirements from customer interviews, online research, standards and technical datasheets, and the requirements checklist. A HOQ organizes design decisions by translating qualitative customer needs into quantitative requirements, identifying relationships and conflicts between metrics, and determining design priorities. The HOQ for the robotic arm is shown in **Figure 2**. The team discovered from the HOQ that designing the robotic arm to meet the customer needs would be complex. All needs required multiple specifications for performance characterization, and these relationships indicated the interconnectedness of the robotic arm's functionalities. This information was relevant to the team when the functional model for the design was developed.

The HOQ identified several critical customer requirements, including lightweight construction, high maneuverability, and durability under harsh conditions. For example, the requirement for "highly maneuverable" was prioritized, necessitating specifications for weight and torque that optimize agility. During the HOQ process, the team encountered tradeoffs between the need for lightweight construction and high torque output. Conflicts such as this one have prompted the need for research into materials to balance these competing needs effectively. The HOQ also highlights a comparative analysis against existing products in the market with available metrics, enabling the team to benchmark performance metrics and identify areas where the arm could improve. The HOQ will be revisited throughout the design process to incorporate feedback from prototyping and user testing. Ultimately, the insights gained from the HOQ will help refine design specifications and enhance product performance.

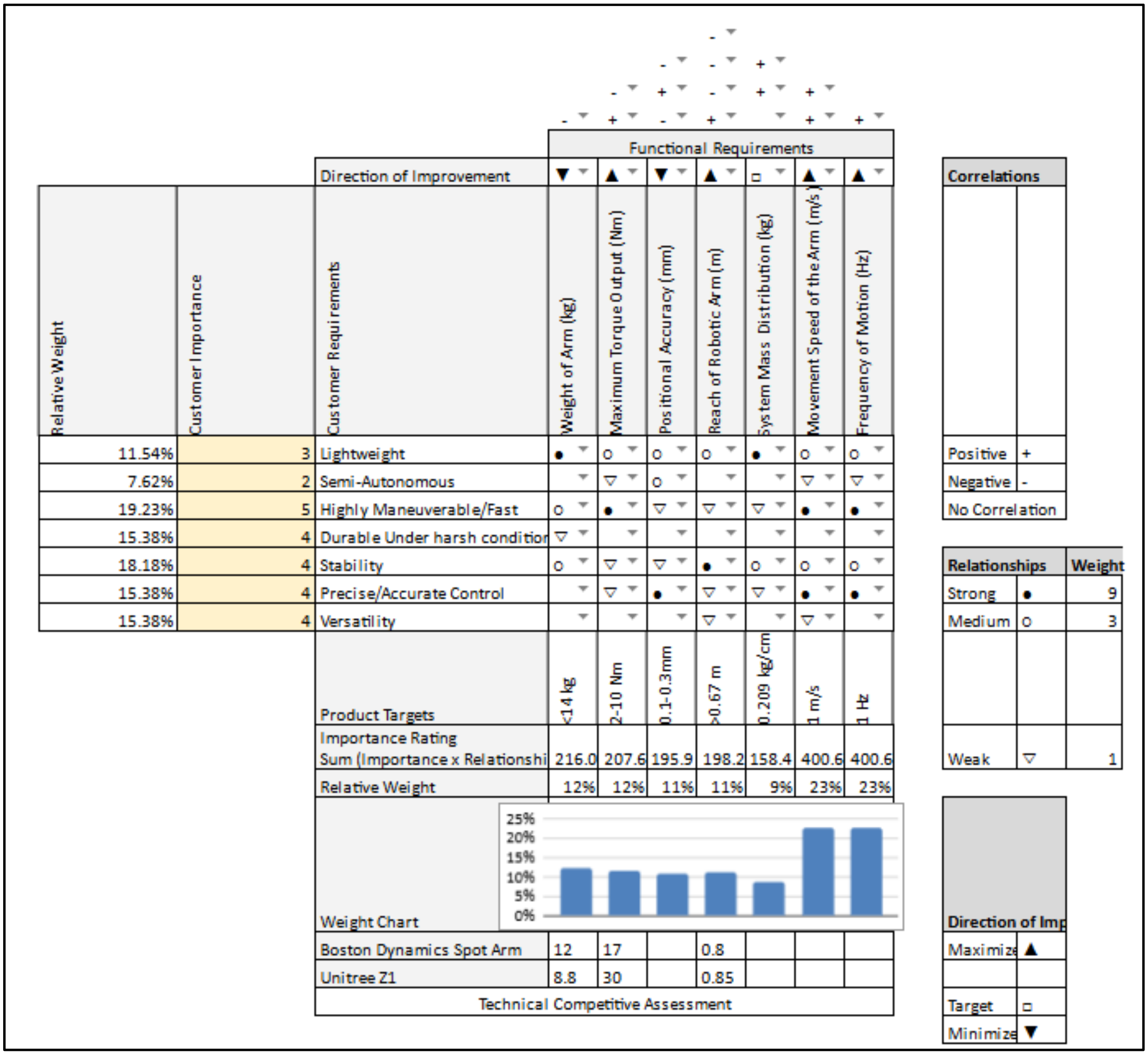


Figure 1:The HOQ relates customer needs to functional requirements, describes how the arm design compares to existing products, identifies functional conflicts, and calculates the relative weights of each functional requirement.

5.3 Requirements Document Table

The specifications documented in the House of Quality (HOQ) are presented in a Requirements Document Table, which serves as an essential tool for cross-referencing requirements with specific customer needs. This table ranks the requirements in order of importance and identifies target values for the design. The Requirements Document Table is shown in **Table 4**. The design team encountered challenges in directly using the importance scores from the Customer Needs Table due to the complexity of the HOQ, which indicated that each customer need corresponds to multiple functional requirements and vice versa. Consequently, a new weighting system was developed by dividing each requirement's Technical Importance Rating from the HOQ by the maximum Technical Importance Rating, multiplying by five, and rounding to ensure consistency with the Customer Needs Table. The resulting weights are generally aligned with the priorities outlined in the Customer Needs Table. The highest weighted requirements included the movement speed of the arm (5), and frequency of motion (5). These weights correlate well with the highly maneuverable/fast (5) and precise/accurate control (4). The analysis indicated that the most significant requirements typically correspond to a larger number of customer needs. This comprehensive analysis of the Requirements Document Table enables the team to evaluate the effectiveness of the robotic arm design in meeting customer expectations accurately.

Table 4: The Design Requirements Table cross-references requirements with the customer needs satisfied. The table provides the importance of each metric as well as the target value.

Requirement #	**Need #**	**Metric**	**Importance Score (1 to 5, 5 = most important)**	**Required Values**	**Units**
1	7,5	Weight of the Arm	3	<14	kg
2	1,2,4	Maximum Torque Output	3	2-10	Nm
3	2,3,8	Positional Accuracy	3	10-30	mm
4	2,5	Reach of Robotic Arm	3	>0.67	m
5	3,5,7	System Mass Distribution	2	0.209	kg/cm
6	1,2	Movement Speed of the Arm	5	1	m/s
7	1,2,3,5	Frequency of Motion	5	1	Hz

6. Functional Modeling

In order to understand what functions needed to be completed by the design, the team developed the Functional Model in phases after finalizing the Customer Needs Table and Design Requirements Table. This model outlines what the proposed robotic arm design aims to achieve using standardized, solution-neutral language. By focusing on this abstraction, the design team enhanced creativity when determining how the product would function, prioritizing customer needs over detailed subsystem specifications. The core of the Functional Model is a set of subfunctions, each directly aligned with a specific functional need. The team followed a five-step process to develop the functional model. The modeling process began with creating a black box functional model, as shown in **Figure 3**. The overall function, derived from the SNPS, was defined as "mimic human arm's dexterity and speed" to ensure the scope was accurate and the model remained solution-neutral. The input and output flows were identified by analyzing the energy, materials, and signals required for the model to fulfill its function. It was determined that electrical and human energy were needed as inputs, while thermal and mechanical (both rotational and translational) outputs were necessary. Additionally, control signals were required for both input and output to align with the position analysis specified in the need statements.

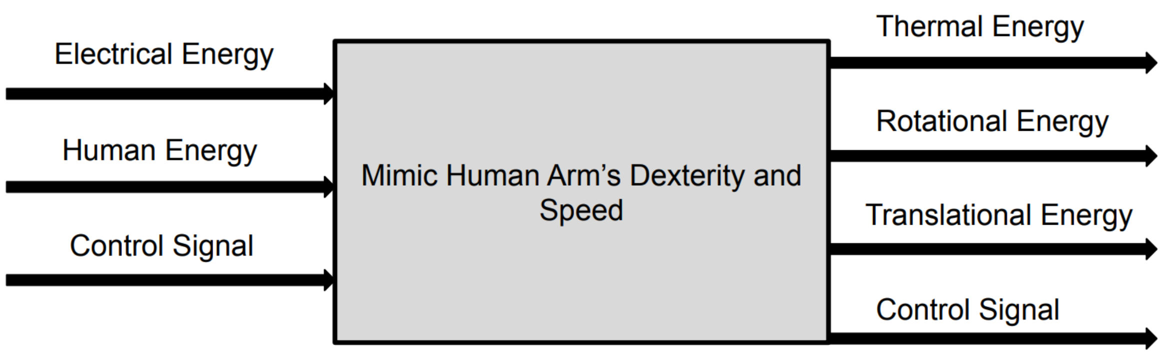


Figure 2: The black box model describes the major functional flows of our robotic arm.

The second step in creating the Functional Model involved linking each customer need from **Table 3** to a corresponding functional flow. The most critical customer needs required mechanical energy, electrical energy, and human energy to drive a robotic arm that emphasized frequency of motion and degrees of freedom. The team then established functional chains by mapping out every operation associated with the identified flow. A comprehensive Functional Model was then produced by merging all subfunction chains into a single diagram (**Figure 4**).

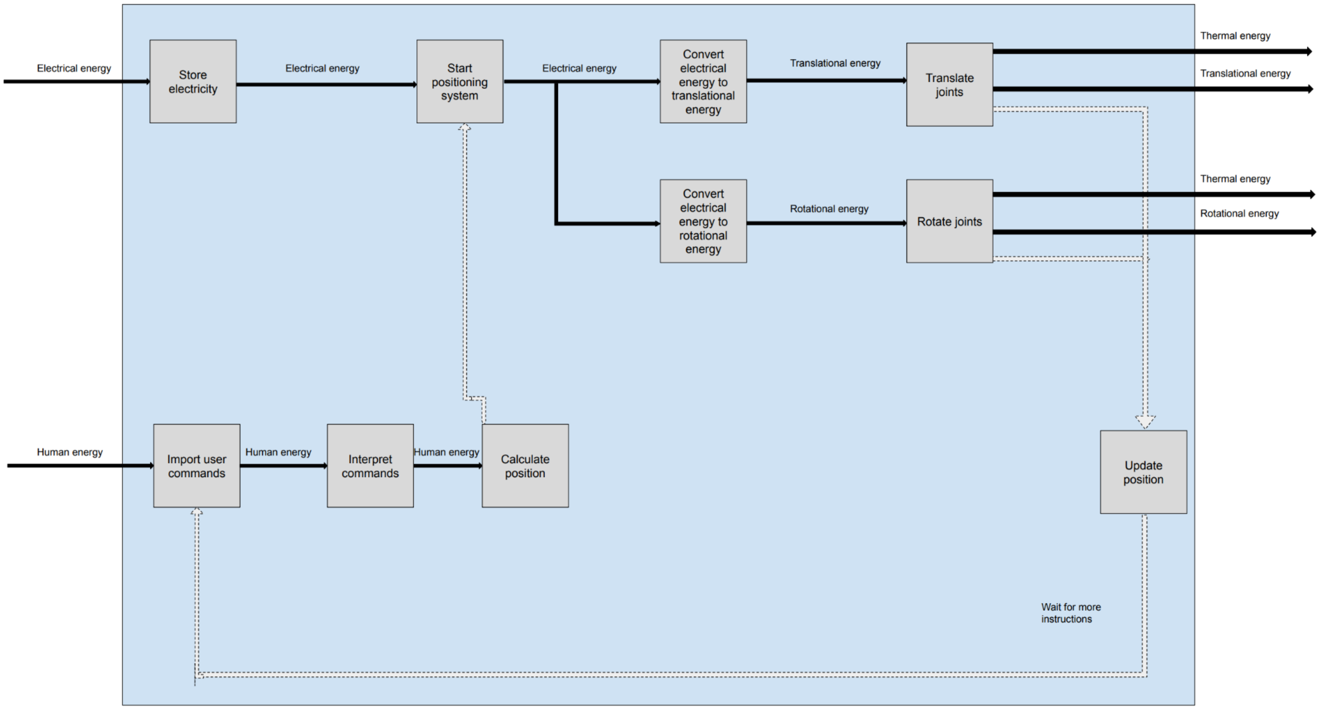


Figure 3: The full functional model describes the major flow in and out of the robotic arm system, the interactions between subfunctions allow the design to achieve the desired function.

The most important functional chain is the top half of **Figure 4** which is responsible for the movement of the robotic arm. This part of the functional model imports electricity that is converted into translational and rotational energy to facilitate the movement of the robotic manipulator.

The final step in developing the Functional Model was to verify that all customer needs were addressed. The team created **Table 5** to illustrate this correlation, showing how each sub-function within the Functional Model modules corresponds to a specific customer need. The numbers in the customer needs column align with those listed in **Table 3**. **Table 5** confirms that the completed Functional Model in **Figure 4** addresses every customer need with at least one subfunction, ensuring the model is comprehensive and well-suited for idea generation.

Table 5: This table illustrates each sub-function cross-referenced to the relevant customer needs.

Sub-Function	Customer Need(s)
Store electricity	6,1,2
Start positioning system	1,2
Convert electrical energy to translational energy	2,3
Translate joints	1,2,4,5
Convert electrical energy to rotational energy	2,3
Rotate joints	1,2,4,5
Import user commands	1,7
Interpret commands	3,7
Calculate position	1,2,3,7
Update position	7

7. Idea Generation

The team utilized a wide variety of idea-generation tactics and techniques to create diverse solutions to the robotic arm design problem. Idea generation techniques are structured methods used to stimulate creativity and develop a wide range of potential solutions to a problem. These techniques help teams or individuals brainstorm, organize, and refine ideas by encouraging innovative thinking, exploring different perspectives, and overcoming mental blocks. The team utilized four different idea-generation techniques to conceptualize the robotic arm. The techniques utilized were brainstorming, the Theory of Inventive Problem Solving (TRIZ), and design by analogy. Finally, a morphological analysis matrix was used to organize ideas based on the subfunctions satisfied.

7.1. Brainstorming

Brainstorming is a creative problem-solving technique used to generate a large number of ideas in a short period of time. This technique encourages open, free-flowing thinking and emphasizes quantity over quality in the initial stages. This fostered creativity and diverse perspectives. The team used brainstorming to produce ideas for how the joints of the robotic manipulator would move. The team brainstormed in a 40-minute session led by Morgan, who facilitated the discussion by recording ideas and encouraging diverse solutions. Each team member came prepared with ideas to serve as a starting point for the brainstorming session. Each idea served as a starting point for the discussion, with team members elaborating on it or offering an alternate idea. This process is illustrated in **Figure 5.**

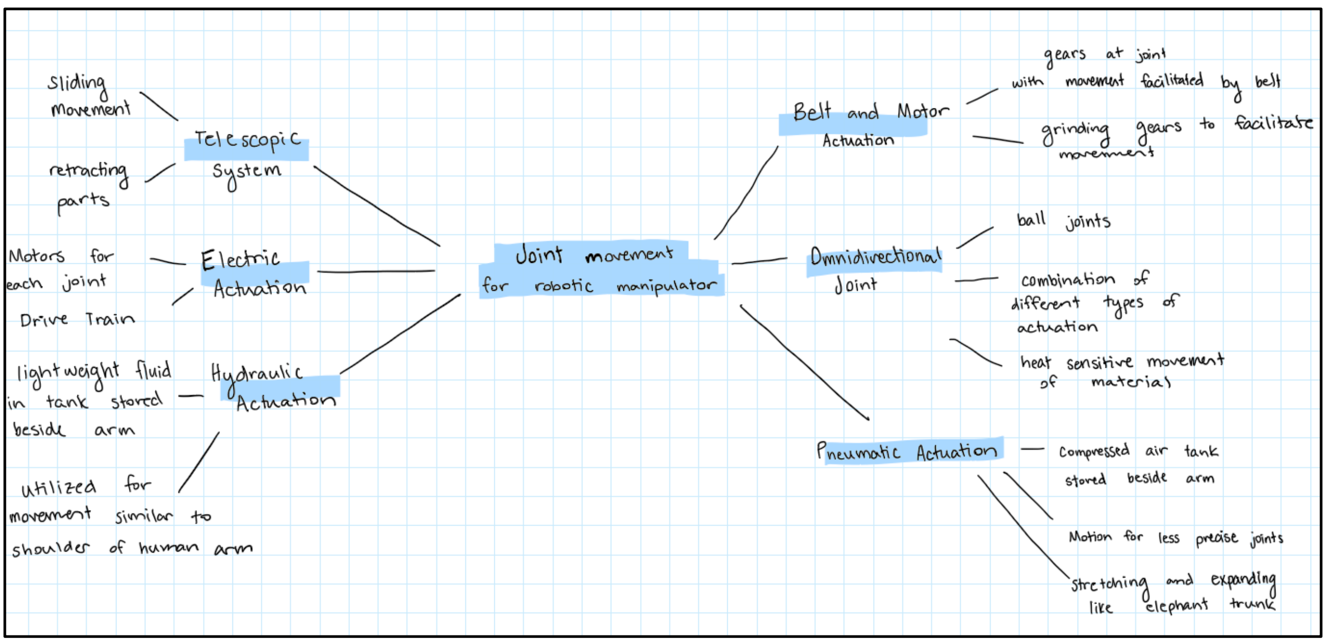


Figure 4: The joint movement systems were categorized by the type of mechanisms that would be implemented to incorporate movement.

The map illustrates the bias towards feasible and conservative ideas when generating ideas. The team took inspiration from pre-existing robots that utilize market motors and actuation devices. The team identified less maneuverable movement that would act as a shoulder or elbow joint for the robotic manipulator with most of the maneuverability occurring at the end point of the manipulator. A few of the innovative ideas that emerged were voice recognition to control the robot and energy harvesting to power it. Energy harvesting is capturing and converting ambient energy from the environment into usable electrical energy, which was inspired by Formula One cars. Brainstorming promoted collaboration within the team and facilitated creative, out-of-the-box thinking.

7.2. Theory of Inventive Problem Solving

The Theory of Inventive Problem Solving (TRIZ) is a structured idea generation method developed by Genrich Altshuller in the 1940's. This method was developed by analyzing patterns in global patent databases. The method is based on the premise that most inventive solutions are not random, but follow certain principles or patterns that can be applied across industries. By focusing on eliminating trade-offs and conflicts within a system, TRIZ fosters breakthrough thinking and drives innovation. The method enabled the team to explore a broader range of solutions while improving efficiency in the problem-solving process. The TRIZ approach involved a five-step process.

For the first step, the team determined the most important conflicts that occurred when designing the robotic manipulator. The conflicts defined were:

1) *Decreasing the weight while increasing the movement speed of the arm*
2) *Decreasing the complexity of the arm while increasing the movement speed of the arm*

Next, these conflicts were formulated in generalized engineering parameters based on **Figure 6** below:

1	Weight of moving object	21	Power
2	Weight of stationary object	22	Energy loss
3	Length of moving object	23	Substance loss
4	Length of stationary object	24	Information loss
5	Area of moving object	25	Waste of time
6	Area of stationary object	26	Quantity of a substance
7	Volume of moving object	27	Reliability
8	Volume of stationary object	28	Accuracy of measurement
9	Velocity	29	Manufacturing precision
10	Force	30	Harmful actions affecting the design object
11	Stress or pressure	31	Harmful actions generated by the design object
12	Shape	32	Manufacturability
13	Stability of object's composition	33	User friendliness
14	Strength	34	Repairability
15	Duration of action generalized by moving object	35	Flexibility
16	Duration of action generalized by stationary object	36	Complexity of design object
17	Temperature	37	Difficulty to control or measure
18	Brightness	38	Level of automation
19	Energy consumed by moving object	39	Productivity
20	Energy consumed by stationary object		

Figure 5: Generalized engineering parameters utilized by the TRIZ method to define conflicts from the first step.

By utilizing **Figure 6** the conflicts were formulated in generalized engineering parameters below:

1) *Decreasing the weight of a moving object (Parameter 1) and increasing the velocity (Parameter 9)*
2) *Decreasing the complexity of the design object (Parameter 36) and increasing the velocity (Parameter 9)*

Next, the team utilized the TRIZ contradiction matrix (**Figure 7***)* to identify the design principles that could be used to generate solutions.

	Worsening Feature / Improving Feature	Weight of moving object	Weight of stationary object	Length of moving object	Length of stationary object	Area of moving object	Area of stationary object	Volume of moving object	Volume of stationary object	Speed	Force (Intensity)	Stress or pressure	Shape	Stability of the object's composition	Strength	Duration of action of moving object	Duration of action of stationary object
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Weight of moving object	+	-	15, 8, 29,34	-	29, 17, 38, 34	-	29, 2, 40, 28	-	2, 8, 15, 38	8, 10, 18, 37	10, 36, 37, 40	10, 14, 35, 40	1, 35, 19, 39	28, 27, 18, 40	5, 34, 31, 35	-
2	Weight of stationary object	-	+	-	10, 1, 29, 35	-	35, 30, 13, 2	-	5, 35, 14, 2	-	8, 10, 19, 35	13, 29, 10, 18	13, 10, 29, 14	26, 39, 1, 40	28, 2, 10, 27	-	2, 27, 19, 6
3	Length of moving object	8, 15, 29, 34	-	+	-	15, 17, 4	-	7, 17, 4, 35	-	13, 4, 8	17, 10, 4	1, 8, 35	1, 8, 10, 29	1, 8, 15, 34	8, 35, 29, 34	19	-
4	Length of stationary object		35, 28, 40, 29	-	+	-	17, 7, 10, 40	-	35, 8, 2,14	-	28, 10	1, 14, 35	13, 14, 15, 7	39, 37, 35	15, 14, 28, 26	-	1, 10, 35
5	Area of moving object	2, 17, 29, 4	-	14, 15, 18, 4	-	+	-	7, 14, 17, 4		29, 30, 4, 34	19, 30, 35, 2	10, 15, 36, 28	5, 34, 29, 4	11, 2, 13, 39	3, 15, 40, 14	6, 3	-
6	Area of stationary object	-	30, 2, 14, 18	-	26, 7, 9, 39	-	+	-		-	1, 18, 35, 36	10, 15, 36, 37		2, 38	40	-	2, 10, 19, 30
7	Volume of moving object	2, 26, 29, 40	-	1, 7, 4, 35	-	1, 7, 4, 17	-	+	-	29, 4, 38, 34	15, 35, 36, 37	6, 35, 36, 37	1, 15, 29, 4	28, 10, 1, 39	9, 14, 15, 7	6, 35, 4	-
8	Volume of stationary object	-	35, 10, 19, 14	19, 14	35, 8, 2, 14	-		-	+	-	2, 18, 37	24, 35	7, 2, 35	34, 28, 35, 40	9, 14, 17, 15	-	35, 34, 38
9	Speed	2, 28, 13, 38	-	13, 14, 8	-	29, 30, 34	-	7, 29, 34	-	+	13, 28, 15, 19	6, 18, 38, 40	35, 15, 18, 34	28, 33, 1, 18	8, 3, 26, 14	3, 19, 35, 5	-
10	Force (Intensity)	8, 1, 37, 18	18, 13, 1, 28	17, 19, 9, 36	28, 10	19, 10, 15	1, 18, 36, 37	15, 9, 12, 37	2, 36, 18, 37	13, 28, 15, 12	+	18, 21, 11	10, 35, 40, 34	35, 10, 21	35, 10, 14, 27	19, 2	
11	Stress or pressure	10, 36, 37, 40	13, 29, 10, 18	35, 10, 36	35, 1, 14, 16	10, 15, 36, 28	10, 15, 36, 37	6, 35, 10	35, 24	6, 35, 36	36, 35, 21	+	35, 4, 15, 10	35, 33, 2, 40	9, 18, 3, 40	19, 3, 27	
12	Shape	8, 10, 29, 40	15, 10, 26, 3	29, 34, 5, 4	13, 14, 10, 7	5, 34, 4, 10		14, 4, 15, 22	7, 2, 35	35, 15, 34, 18	35, 10, 37, 40	34, 15, 10, 14	+	33, 1, 18, 4	30, 14, 10, 40	14, 26, 9, 25	
13	Stability of the object's composition	21, 35, 2, 39	26, 39, 1, 40	13, 15, 1, 28	37	2, 11, 13	39	28, 10, 19, 39	34, 28, 35, 40	33, 15, 28, 18	10, 35, 21, 16	2, 35, 40	22, 1, 18, 4	+	17, 9, 15	13, 27, 10, 35	39, 3, 35, 23

Figure 6: TRIZ contradiction matrix that identifies design principles based on conflicts defined in generalized engineering parameters. The worsening feature is identified in the appropriate column while the improving feature is identified in the appropriate row.

The principles that applied to the first conflict are defined in the table below:

Table 6: This table illustrates each design principle which is defined by the TRIZ parameters and principles, and organizes it with the correct conflict.

Conflict	Principals
1	2: Taking out
	28: Mechanics substitution
	13: 'The other way round'
	38: Strong oxidants
2	28: Mechanics substitution
	4: Asymmetry
	10: Preliminary action

To reduce the weight while increasing the movement speed of the arm the team chose to utilize design principles 28 and 13 (**Table 6**). **Design principle 28 (Mechanics substitution)** encourages the use of electric, magnetic, and electromagnetic fields to control or interact with objects, or the combination of such fields with field-activated particles. Leveraging this principle, the team explored various innovative ideas, including utilizing electromagnets for arm movement. This concept involves generating controlled magnetic fields to manipulate or propel the arm segments without relying on traditional mechanical actuators. Another idea was to heat certain materials within the arm, enabling changes in material properties, such as softening or contracting, which could potentially facilitate smoother or faster movement. Both approaches aim to replace heavy mechanical components with field-based mechanisms, reducing the overall weight while optimizing motion efficiency. **Design principle 13 ('The other way round')** focuses on reversing the typical roles of movable and fixed parts within a system. Applying this principle, the team generated several novel ideas, such as using flexible materials at fixed joints, allowing the arm to bend and flex without traditional hinges or actuators. This approach not only simplifies the mechanical structure but also reduces the need for complex moving parts, thereby improving durability and lowering the overall system weight. Another concept involved keeping the arm segments stationary while enabling movement through the base, shifting the mobility from the arm itself to its foundation. This innovative reconfiguration would help achieve smoother and faster movement while maintaining structural simplicity.

To further streamline the design and enhance the arm's movement speed, the team adopted **Design Principle 4 (Asymmetry)**. This principle involves transforming a symmetric design into an asymmetric one to unlock functional advantages. The team conceived ideas such as telescoping translational movement, where the arm could extend or retract in a non-uniform manner, making it adaptable to different operational needs. Another idea focused on fluid dynamics, where the arm's internal flow could be manipulated to alter its stiffness or length. By adjusting the flow properties or incorporating variable pressure zones, the arm could become more rigid for precise tasks or lengthen to reach distant objects.

7.3. Design by Analogy

Design by analogy is an idea generation method that involves drawing inspiration from solutions in other fields or natural systems to solve a design problem. By identifying similarities between the present challenge and analogous situations in unrelated domains, designers can leverage proven principles and approaches to generate innovative concepts. For example, engineers might study how birds fly to improve aerodynamic designs in aviation or explore how plants conserve water in arid environments to develop more efficient irrigation systems. This method stimulates creative thinking by encouraging designers to look beyond traditional boundaries and apply diverse knowledge to their challenges. To generate unique design ideas the team brainstormed analogies to take inspiration from. First, the team generated a list of possible machines, systems, and animals that could provide solution inspiration. The team chose to research the topics of an elephant trunk and a human arm. Once the list was created, the team researched each respective topic.

For the elephant trunk, the approach began with reviewing articles on 'asknature.org' to identify other inventions that take inspiration from an elephant trunk. The team found a Bionic Handling Assistant which is a robotic arm inspired by the dynamic motion and gripping ability of an elephant's trunk [21]. Like the trunk, which can move in various directions with strength and precision due to its structure of tightly packed muscle fibers, the robotic arm achieves a wide range of motion through its three interconnected segments. These segments are filled with compressed air, allowing lightweight and flexible movement, with the entire arm weighing just 5 lbs. Sensors within the arm help control its precise movements. At the end of the arm, a gripper with three flexible claws molds to the shape of objects, making it easier to grip and hold them securely. Drawing inspiration from the extension movements of an elephant's trunk, the robotic arm can also extend to reach distant objects, enhancing its versatility as seen in **Figure 8** [22].

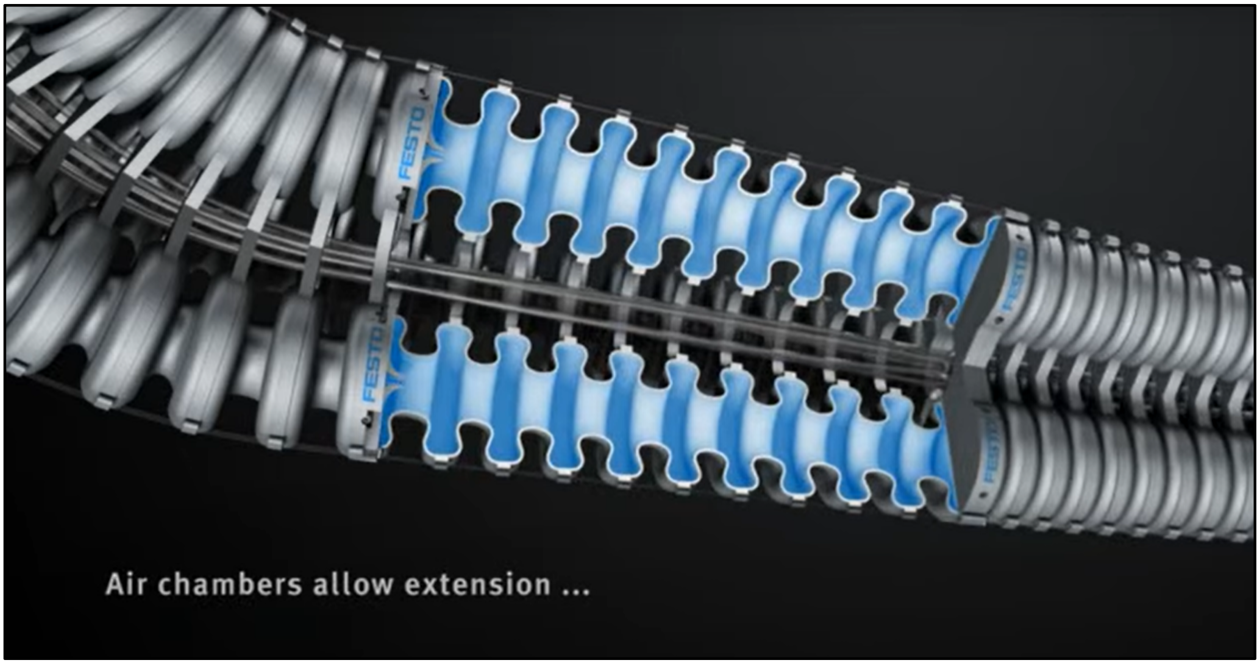


Figure 7: Bionic Handling Assistant robotic arm made up of chambers of compressed air, which allow for a wide range of motion.

In the field of bio-inspired robotics, the human arm and hand serve as powerful models for developing advanced robotic systems that replicate natural movement and dexterity. The human arm's structure, including its seven degrees of freedom—enabled by the shoulder, elbow, and wrist—offers inspiration for robotic designs that mimic its rotational and multi-axis capabilities. The shoulder, for instance, allows for a wide range of rotational motion, a feature crucial for creating flexible and versatile robotic arms.

A prime example of this approach is found in the work of Pollard's lab, which captures detailed videos of how a human hand grasps and manipulates objects [23]. These hands use actuators as artificial tendons to enable movement. To further enhance the function of these robotic hands, Alamgir Karim’s lab at the University of Houston focuses on using low-voltage electric fields to control soft polymers that mimic muscle movements. His team has identified triblock copolymers that can operate actuators on as little as a 10-volt battery, presenting a promising solution for low-energy robotic applications.

Inspired by the natural dynamics of the human arm, Festo's Bionic Handling Assistant emulates human bones and muscles using pneumatic actuators that allow for fluid, coordinated movement [24]. This robotic arm, like its biological counterpart, is equipped with a complex bone structure and muscles that enable it to lift loads, move with precision, and grip objects securely. With 64 muscles, 28 bones, and various sensory receptors, the human arm can perform tasks ranging from throwing a baseball at 150 km/h to lifting weights of up to 250 kg.

The integration of such bio-inspired elements into robotics not only enhances movement fluidity and force control but also enables robots to adapt to a wide range of tasks, from handling delicate objects to performing high-force activities. This approach opens up new possibilities in fields requiring precise, adaptable, and energy-efficient robotic systems. The team can take inspiration from these designs and utilize actuation to create muscle-like movement.

7.4. Morphological Analysis Matrix

The final phase of idea generation was morphological analysis which is a structured method used to explore all possible solutions by breaking it down into its fundamental components. This technique encourages creative thinking by systematically examining the relationships between the different parameters of a problem. The process involves identifying key functions or characteristics of the product and listing potential solutions or options for each function. These solutions were created through the 3 idea generation methods chosen by the team. Some subfunctions had a limited range of solutions to satisfy them. For example, the subfunction "start positioning system" only contained one solution which was the implementation of wires. By combining different options across parameters, the Morphological Analysis Matrix generates a wide range of potential design concepts. The team's final morphological matrix is displayed in **Table 7.**

Table 7: The Morphological Matrix organizes ideas generated by each sub-function that needs to be fulfilled. A complete concept is then generated by choosing a solution for each of the required subfunctions.

Subfunction	**Solution**						
Store Electricity	Rechargeable/ Primary Batteries	Capacitors	Cable connection	Wires	Energy Harvesting		
Start positioning system	Wires						
Convert electrical energy to translational energy	Motor	Actuator	Gears	Drive Train			
Translate joints	Pulleys	Omnidirectional joint	Telescoping system	Actuation	Heat-sensitive movement of material	Magnetic levitation	Compressed air like elephant trunk or hose
Convert electrical energy to rotational energy	Motor	Actuator	Gears	Drive Train			
Rotate joints	Pulleys	Ball joint	Combining different actuators	Gimbal Mechanism	Magnetic Couplings		
Import user commands	Arduino	Raspberry Pi	Bluetooth	Pre-programmed commands	Voice Recognition	Gesture Recognition	
Interpret commands	Python	C++	MATLAB	Simulink			
Calculate position	Inverse Kinematics	Forward Kinematics					

8. Concept Refinement

8.1 Concept Definition

Analyzing the range of possible solutions for each sub-function within the Morphological Matrix resulted in the development of several well-defined and technically feasible concepts for the robotic arm. **Table 8** outlines the four key concepts that emerged from this process. Distinct solutions were chosen to address each specific subfunction. This systematic approach allowed for the identification of diverse and feasible options. Certain subfunction solutions appeared more viable than others, and the team wanted to incorporate realistic solutions that could be achieved within the normal capstone time frame. Our final designs needed to satisfy the requirements of being able to achieve a frequency of movement of around 1 Hz and reach a minimum workspace of 67 cm.

Table 8: The Morphological Matrix was utilized to create four concepts that fulfilled each necessary subfunction.

	Solution			
Subfunction	**Concept 1**	**Concept 2**	**Concept 3**	**Concept 4**
Store Electricity	Batteries	Cable Connection	Batteries	Cable Connection
Start positioning system	Wires	Wires	Wires	Wires
Convert electrical energy to translational energy	Gears and Motors	Actuator	Motor	Actuators and Motors
Translate joints	Pulleys	Telescoping System	Actuation	Telescoping System
Convert electrical energy to rotational energy	Motor	Motor and Actuator	Motor	Motor
Rotate joints	Gimbal Mechanism	Ball Joint	Actuation	Ball Joint
Import user commands	Raspberry Pi	Bluetooth	Raspberry Pi	Raspberry Pi
Interpret commands	Python	C++	Python	Python
Calculate position	Inverse and Forward Kinematics	Inverse Kinematics	Inverse Kinematics	Inverse Kinematics

8.2. Detailed Sketches

Table 8 provided a strong foundational framework for refining and ultimately selecting concepts. Each subfunction identified in the Functional Model was linked to a corresponding solution, allowing the team to rapidly develop detailed schematics. These drawings offered multiple proofs of concept with sufficient detail for engineering calculations and feasibility assessments. This work advanced the project by transforming abstract ideas into concrete designs.

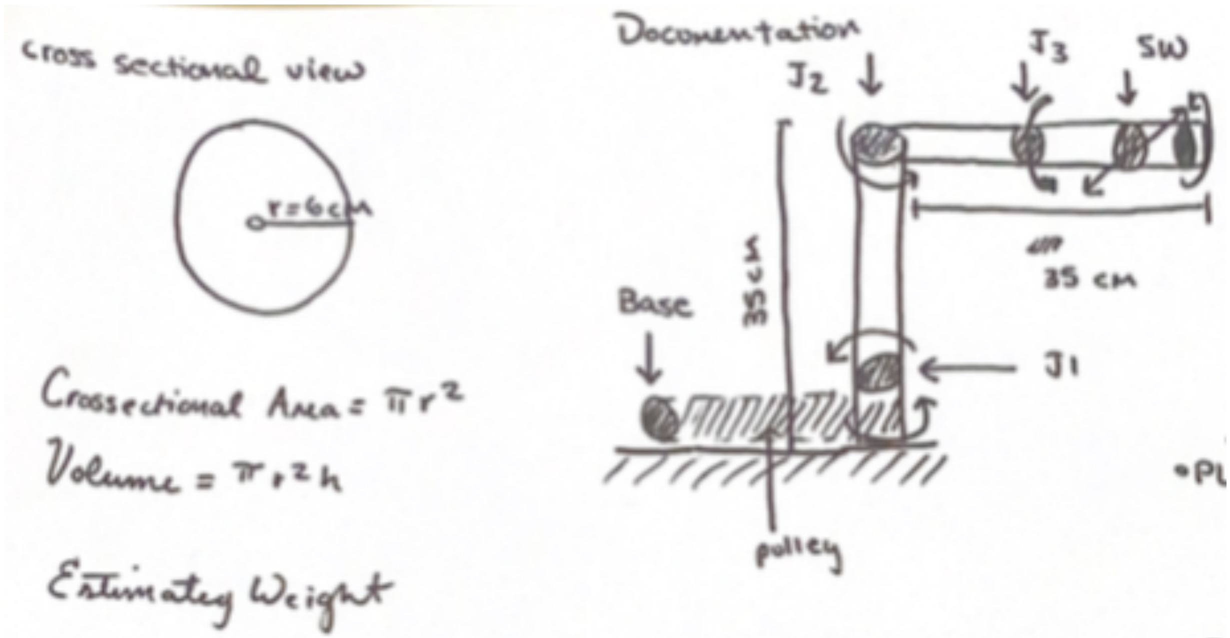


Figure 8: Concept 1 Sketch

Figure 9 Concept 1 is a sketch of a 6 Degree of Freedom robotic arm. This design is a robotic arm powered by six rotary joints, with each joint being driven by a motor. The body of the arm is constituted of a rod in cylindrical shape, attached via a rotary joint to the base and an offset pulley-motor system is used for the rotation of the arm in z normal to the base. Joints 1 and 2 are the translation motors, while Joint 3 controls rotation for the spherical wrist. For its actuation, the spherical wrist has two other motors. The mean human arm radius was found to be 12 cm; this was then divided by two to satisfy the design specification of a 1:2 relationship of the prototyped robotic arm, as directed by the project sponsor. The length of the arm was specified to be 70 cm. Following a detailed analysis in Appendix F, the base motor chosen is the Kollmorgen AKM Series Servomotor, and the other five motors are identified as MG996 Servo Motors. The material to be used for the manufacture of this design is PLA due to low cost and availability, and also because it has good enough tensile strength for the application. The selection of motor chosen for this particular robot design was based on the detailed requirements of the robot: RPS, torque, size, weight, cost, and frequency of the motor. A detailed explanation of these is found in **Appendix F.**

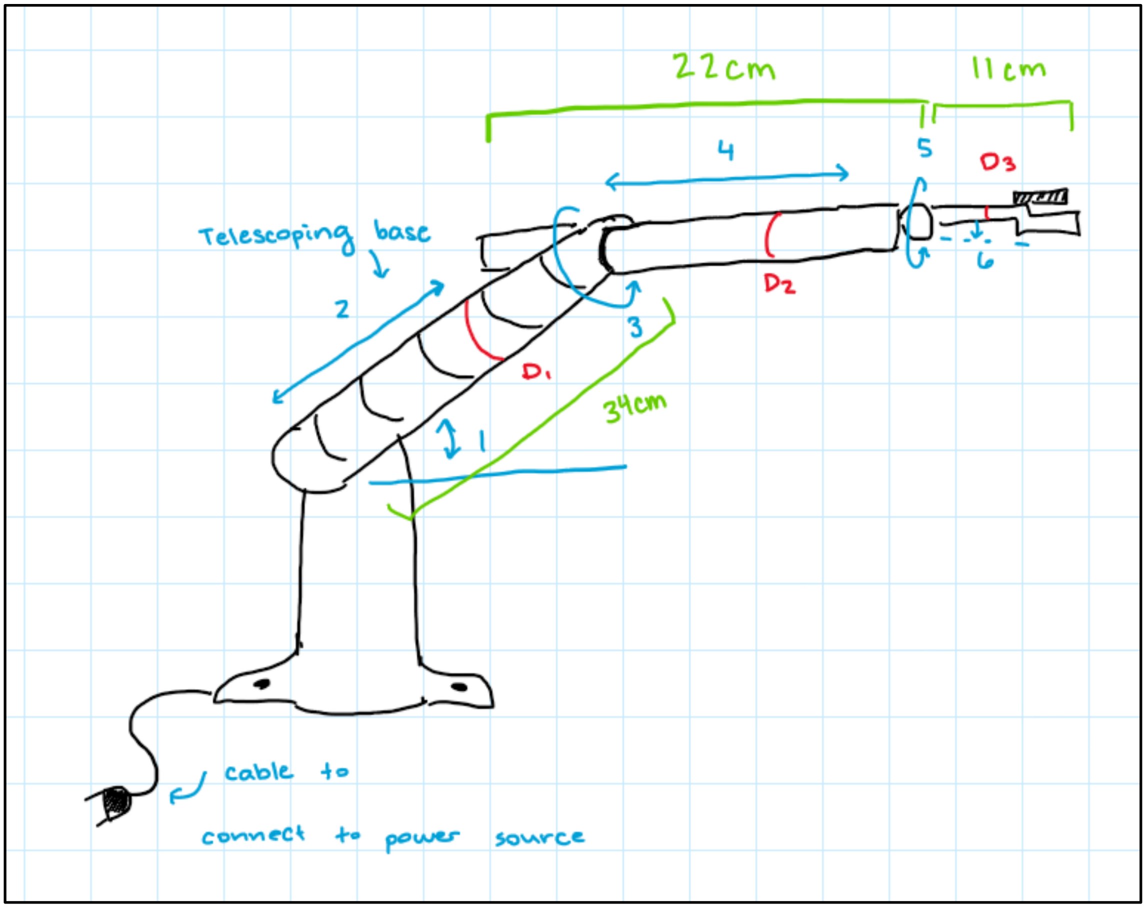


Figure 9: Concept 2 Sketch

Figure 10 is a sketch of a 6 Degree of Freedom robotic arm representing the solutions of concept 2 in the morphological matrix. This concept takes inspiration from the Stanford Robotic Manipulator to achieve movement. This concept utilizes both stepper motors and actuation to create movement. It has four NEMA 17-stepper motors and two NOOK Programmable Linear Actuators to create movement. It has a total weight of 13.24 kg and a reach of 67 cm. The maximum torque output of this concept is 2.8 Nm which is smaller than the other concepts. This is due to 2 degrees of freedom coming from linear actuation which does not have a torque output. Positional accuracy is maintained within a 10-30 mm range, as requested by our sponsor. The arm operates at a motion frequency of 25 Hz, to allow fast movement. All structural components are designed to be 3D printed with PLA, which allows easy and rapid prototyping, and has enough tensile strength for the application. This mechanism is powered by a cord connected to a power source and control managed via Python on a Raspberry Pi. Engineering specifics and calculations are detailed in **Appendix F**.

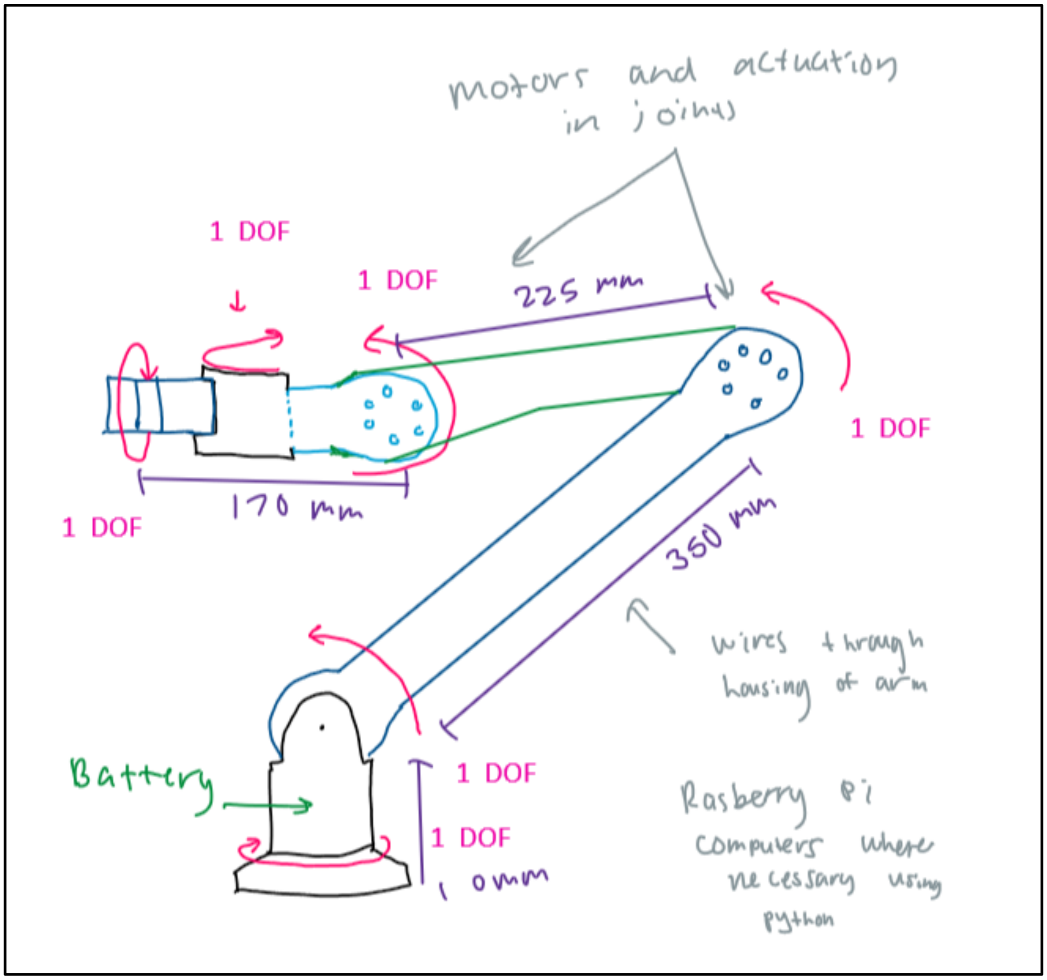


Figure 10: Concept 3 Sketch

Figure 11 is a conceptual sketch for a 6 DoF arm. This concept takes inspiration from arms seen on the market currently, This design utilizes six NEMA 24-stepper motors and achieves a total weight of 9.08 kg. The NEMA 24 motors balance size and torque, ideal for a 6DOF arm [12]. The arm offers a maximum torque output of 5.21 Nm and a reach of 0.74 m, making it slightly longer than the other concepts. Positional accuracy is maintained within a range of 10-30 mm per our sponsor's request. The arm operates at a motion frequency of 1 Hz, providing steady and controlled movements. All structural components are planned to be 3D printed using ABS filament for enhanced durability and heat resistance. Power for the system is supplied through batteries, while the programming and control are handled using Python on a Raspberry Pi. Engineering details and calculations can be found in **Appendix F.**

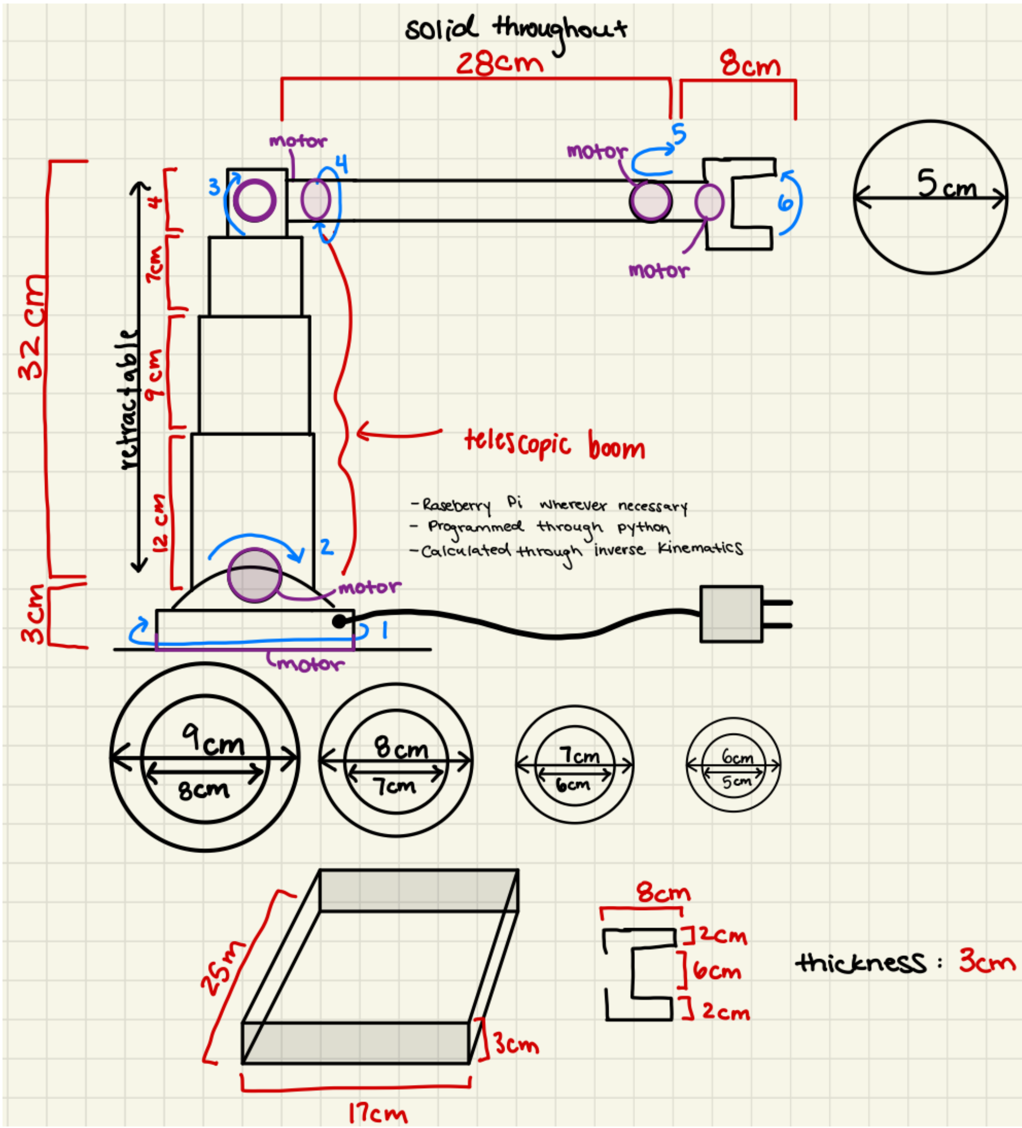


Figure 11: Concept 4 Sketch

Figure 12 outlines the sketch made for concept 4. In summary, this concept includes 6 Degrees of Freedom, 2 in the shoulder joint, 2 in the elbow joint, and 2 in the wrist joint. Another key feature of this arm is that it includes a telescoping bicep component, allowing the arm to move vertically up and down. This was also included for storage purposes. The Degree of Freedom in the shoulder joint includes a 360° rotation as well as a side-to-side motion. The elbow joint includes very similar Degrees of Freedom, except the side-to-side motion is now an up-and-down motion. Lastly, the wrist includes two Degrees of Freedom, one 360° rotation and the other having the ability to move up and down which will also allow it to move left and right when rotated. These 6 DoF points were included to ultimately resemble the movement of a human arm. All linkages are planned to be 3D printed using PLA filament and the dimensions were based on the average size of a male human arm. The motor that was chosen was a stepper motor that averaged 0.45kg, 0.65 Nm torque, and a rotation of 100 r/min. This arm plans to be powered through an electrical cord connected to an outlet and programmed using python and raspberry pi. All engineering calculations and estimates can be found in **Appendix F**.

9. Concept Selection

9.1 Selection Criteria

To select the team's final design, a Pugh chart and Quantitatively Driven Team Effort Selection Matrix (QDTESM) were used to compare the four concepts created. The Customer needs table seen in **Table 3** was used to determine the weights and requirements needed for the Customer Requirements seen within the Pugh chart and the Functional Requirements seen in the QDTESM. The customer requirements that were used included highly maneuverable/fast, precise/accurate control, versatile, durable under harsh conditions, stable, lightweight, and semi-autonomous. All of the weights associated with each criterion were based on the HOQ weight percentage values which took outside expert opinions into high consideration. The functional requirements used included the weight of the arm (kg), the maximum torque output (Nm), the positional accuracy (mm), the reach of the robotic arm (m), and the frequency of motion (Hz). These weighted values were taken from the HOQ and the team's engineering judgment for the needed performance of the arm.

9.2 Pugh Chart

The team used a Pugh chart to compare each of the four individual concepts against a baseline, evaluating how well they met the customer needs. A Pugh chart is defined as a tool used in decision-making processes, especially in engineering and product development, to compare multiple design alternatives against a set of criteria. The process taken to use a Pugh chart includes 1. Determining the selection criteria, 2. Determining the alternatives, 3. Rating and ranking the alternatives, 4. Evaluating the results, and 5. Acknowledging and understanding the limitations. The selection criteria were based on the Customer Needs and were used to rate each selection criterion for each concept ranging from -2 to +2, corresponding to whether the concept was performing better, the same as, or worse than the selected datum design. Once each criterion for each design was rated, they were multiplied with their corresponding weights and summed to generate each concept's total scores. When using this method, many advantages and disadvantages are present. A major advantage to using a Pugh chart is the organization and visibility that it gives when needed to compare four individual designs based on 7 different criteria. The visibility of it stems from clearly being able to see why one design is better/worse when compared to the other based solely on what the customer needs. On the other hand, a disadvantage when using a Pugh chart is that all the ratings and weights for each criterion are very subjective, allowing individuals to decide which concept is best based on their judgment. Additionally, one design is ultimately thrown out as being the datum since all its criteria are set to zero. In an attempt to limit the team's bias, the weights were determined using professional feedback from surveys and interviews.

The complete Pugh chart for the Human Robotic Arm can be seen in **Table 9**. Concept 3 was chosen to be the baseline design, labeled Datum since it is the most similar to already on-the-market robotic arm designs. The datum design had all scores of zero. Based on the results, it was found that concept 4 had the highest score of 0.2867 while concepts 1 and 2 scored -0.6817 and -1.1326, respectively. Overall, concept 4 scored the highest because it was the most stable and lightweight while concept 1 and 2 scored the worst because mostly all their criteria were worse when compared to concept 3. The overall design that scored the best was lightweight, fast, and stable which Concept 4 was able to attain.

Table 9: Pugh Chart used to compare each concept's performance to the criteria from the Customer Needs Table.

Selection Criteria	Weight	Concept 1	Concept 2	Concept 3 (Datum)	Concept 4
Highly Maneuverable / Fast	0.1154	0	2	0	1
Precise/Accurate Control	0.0762	0	0	0	0
Versatile	0.1923	-1	-2	0	-1
Durable under harsh conditions	0.1538	-1	-1	0	-1
Stable	0.1818	-1	-2	0	2
Lightweight	0.1538	-1	-2	0	2
Semi-Autonomous	0.1538	0	-1	0	-1
Sum		-0.6817	-1.1326	0	0.2867

9.3 Quantitatively Driven Team Effort Selection Matrix

Continuing with the concept selection process, the team used a Quantitatively Driven Team Effort Selection Matrix (QDTESM) to compare all the concepts on more quantified criteria rather than qualitative criteria. This selection method adds the benefit of comparing each concept based on calculated values through engineering analysis which allows the team to compare based on performance. The parameters used were slightly different than the ones seen in the HOQ to allow all designs to have calculated values to compare. This was set in place to be uniform across all designs, allowing the team to have the same criteria per design. The set of parameters used includes the weight of the arm (kg), maximum torque output (Nm), positional accuracy (mm), the reach of the robotic arm (m), system mass distribution (kg), movement speed of the arm (m/s), and frequency of motion (Hz). All these values were estimated based on personal research and engineering approximations. The values for each concept can be seen in **Table 10**.

Table 10: Functional Requirement Values for each concept.

Functional Requirements	Concept 1	Concept 2	Concept 3	Concept 4
Weight of Arm (kg)	10.67	13.24	9.08	5.723
Maximum Torque Output (Nm)	5.83	2.8	5.21	3.9
Positional Accuracy (mm)	10-30	10-30	10-30	10-30
Reach of Robotic Arm (m)	0.7	0.67	0.74	0.71
Frequency of Motion (Hz)	1	25	1	1.67

Since these sets of parameters don't have the same units, a scaling measure was needed to be performed by converting the calculated values based on the worst given a score of 0 and the best given a score of +1. The other two values for the concepts were then linearly interpolated based on their value between 0 and 1. Once converted to scalable values, each number was multiplied by each criteria weight and summed together to find each concept rating. The resulting data can be seen in **Table 11. Table 11** expresses the concept evaluation of the QDTESM based on specific selection criteria outlined by the team, and seen tabulated in the Selection Criteria portion of the table. Furthermore, the team used a deductive reasoning process to determine the Criteria Importance based on the HOQ metrics in **Figure 2**. The raw score was derived from the scalable functional requirement values for each concept and adjusted based on the criteria importance selection from the HOQ. This adjusted score was then multiplied to generate the weighted score for each specific selection criterion, which was summed to form the basis for our concept selection.

Table 11: Concept Evaluation using the QDTESM.

Selection Criteria	Criteria Importance	Concept 1		Concept 2		Concept 3		Concept 4	
		Raw	Weighted	Raw	Weighted	Raw	Weighted	Raw	Weighted
Weight of Arm (kg)	0.3	0.658	0.197	0.0	0.0	0.447	0.134	1.0	0.3
Maximum Torque Output (Nm)	0.1	1.0	0.1	0.0	0.0	0.795	0.080	0.363	0.036
Positional Accuracy (mm)	0.05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Reach of Robotic Arm (m)	0.15	0.429	0.064	0.0	0.0	1.000	0.150	0.571	0.086
Frequency of Motion (Hz)	0.4	0.0	0.0	1.0	0.4	0.0	0.0	0.028	0.011
Total	1	0.362		0.400		0.364		0.433	

The QDESTM indicated that Concept 4 performed the best among all the criteria. Concept 4 clearly ranked higher than other designs due to its low weight and high frequency of motion. These metrics with their high weighting made Concept 4 come out on top in this competition among the concepts 1-4. Concept 1 and Concept 2 performed somewhat decently, the two concepts have competitive overall scores mainly due to decent total time per adjustment and good positioning metrics, but not quite as high as those of Concept 4 in the high-impact areas. On the other hand, Concept 3 had the poorest values for most attributes: its heavier design, with less torque output and slower adjustment times meant that with high weights assigned to these criteria, the score was considerably lower in the QDTESM evaluation.

9.4 Final Concept Selection and Results Discussion

Ultimately, the team selected concept 4 as the final concept because concept 4 scored highest on the QDTESM and the Pugh chart. Concept 2 had a very similar score on the QDTESM but scored the worst on the Pugh chart. The subjective criteria of the Pugh chart correspond directly with the stated customer needs and therefore merits consideration. Due to this, the team could not consider concept 2 and concept 4 became the strongest candidate for consideration. The preliminary CAD model of concept 4 is shown below. **Figure 14** clearly labels each degree of freedom present in the robotic arm.

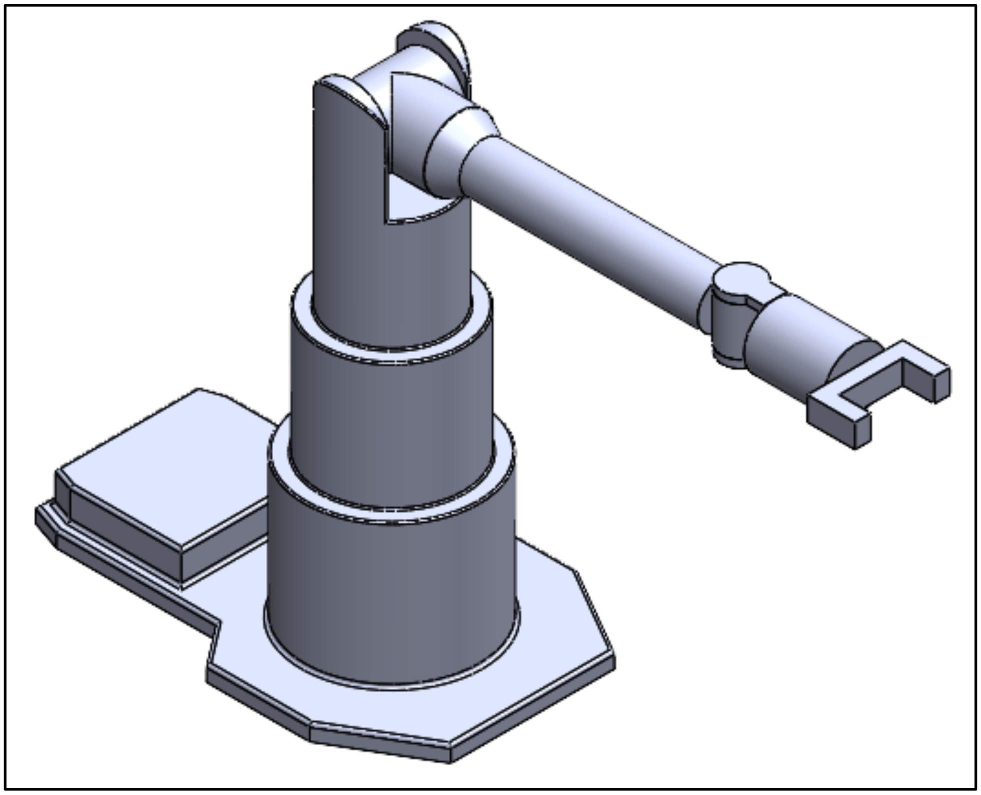


Figure 12: Preliminary SolidWorks assembly of final design concept (concept 4).

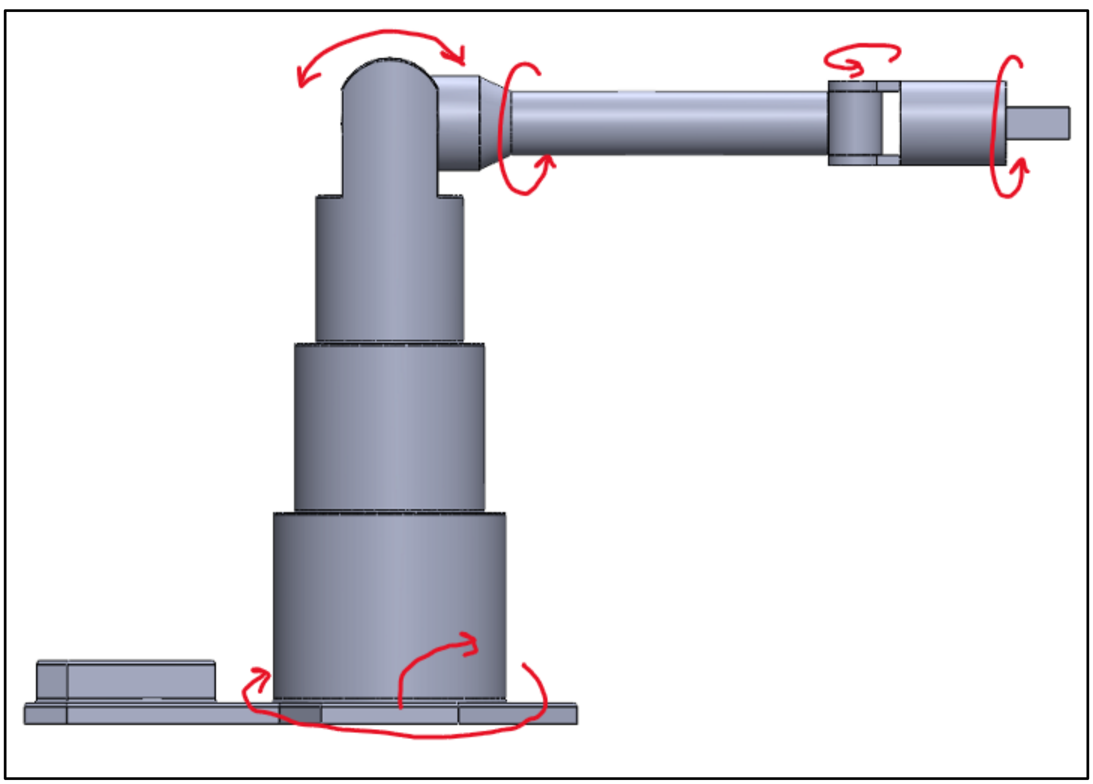


Figure 13: Preliminary SolidWorks assembly of final design concept with DoF arrows (Concept 4).

10. Embodiment Design

10.1 Product Architecture

The purpose of Product Architecture is to generate a general design and structure of a product that defines how components and modules interact to deliver the product's functionality. This includes the hardware and software layout, which describes the key features and functions of the product and their interrelations. It's important to note that a well-thought-out product architecture plays a major role in guaranteeing the efficiency, scalability, and maintainability of the product throughout its life, serving as a guideline for development. Effective product architecture emphasizes modularity: modules and subsystems function independently with clear roles. This promotes a balance between complexity and manageability, making development easier and leading to a robust and adaptable product.

10.1.1 Modules

The product architecture for the human-robotic arm is organized into key functional modules that interact to achieve overall system functionality as seen in **Figure 15.** These modules and their components are designed to work together efficiently while maintaining their modularity.

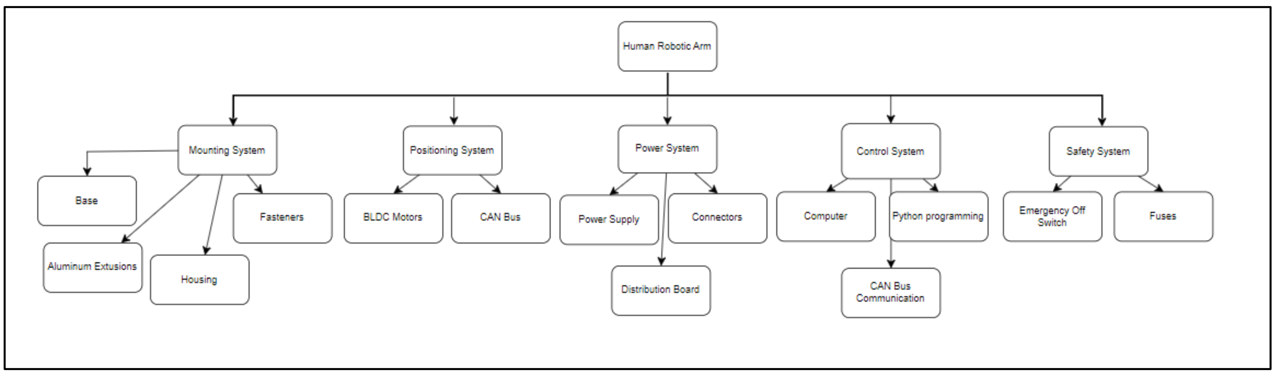


Figure 14: Product Architecture Hierarchy Diagram representing the Robotic arm system modules along with Subfunctions

1. Mounting System – The mounting system serves as the foundational structure of the robotic arm, providing stability and support for all other components. It includes the base, aluminum extrusions, and housing, which are designed to securely attach the robotic arm to the 3D-printed base. This module must be robust enough to withstand the forces exerted during arm movements while maintaining the precision needed for delicate tasks. The base design will utilize a minimum of 12 fasteners to secure the base to aluminum extrusions. The first motor will also be secured to the 3D-printed base. The motor mounts will be reinforced and are designed to handle higher torque loads without compromising precision. Additionally, the modularity of the design allows for future upgrades or changes to the configuration of the arm.
2. Positioning System – The positioning system is responsible for controlling the arm's movement through its multiple degrees of freedom (DOF). This system integrates Brushless DC motors with encoders to provide precise position control. The motors' movement is governed by feedback received from the encoders, which ensures that the system continuously monitors and adjusts the arm's position in real-time. Each motor, associated with a specific joint, operates in unison with the other motors to achieve coordinated movements, ensuring the arm moves as intended. The CAN bus system allows for efficient communication between motors, which are daisy-chained to ensure

smooth movements. Daisy chaining the CAN bus allows for efficient data communication between all connected motor controllers without the need for individual connections to the central processor.

3. Power System – The power system is responsible for supplying the necessary voltage and current to the robotic arm. It consists of a power supply, distribution board, and connectors. Our sponsor plans on providing the 9115B Bench Power Supply which will be used to provide adjustable voltage and current to the system, ensuring that each motor receives the appropriate power levels for its operation. The distribution board will distribute power to different components with the appropriate current and voltage. The system is designed to be flexible, as the power supply can be adjusted to different voltage and current levels depending on the requirements of the components.
4. Control System – The control system is the central brain of the robotic arm, responsible for interpreting inputs and processing them to control the movement of the motors via the CAN bus. The control system will be based on a central processor which sends commands through the CAN bus to each motor's controller. The computer will use Python as the programming language to interact with the hardware. The python code will interface with the robotic arm's CAN bus, sending commands to each motor's controller to control the joint movements, such as position, speed, and torque.
5. Safety System – The safety system includes the emergency off switch the team is planning to implement. An emergency stop feature will allow the operator to stop all movements immediately in case of an emergency. Each motor will be equipped with a fuse to protect the motor and associated wiring from overcurrent situations that could be dangerous and pose a fire hazard. The fuses will act as a fail-safe in the event of a short circuit or excessive current draw.

10.1.2 Product Architecture: Geometric Diagram

The Geometric Diagram plays a crucial role in showing various aspects of module relationships, including material flow, energy transmission, information signaling processes, and spatial considerations such as geometric dimensions, degrees of freedom, tolerances, and constraints. By visualizing these elements, the diagram acts as a roadmap, providing a clear and concise overview of the structural and functional details within the product architecture. It serves as a useful tool for designers, engineers, and stakeholders, to gain a deeper understanding of module interdependence and guide the development and optimization of a system.

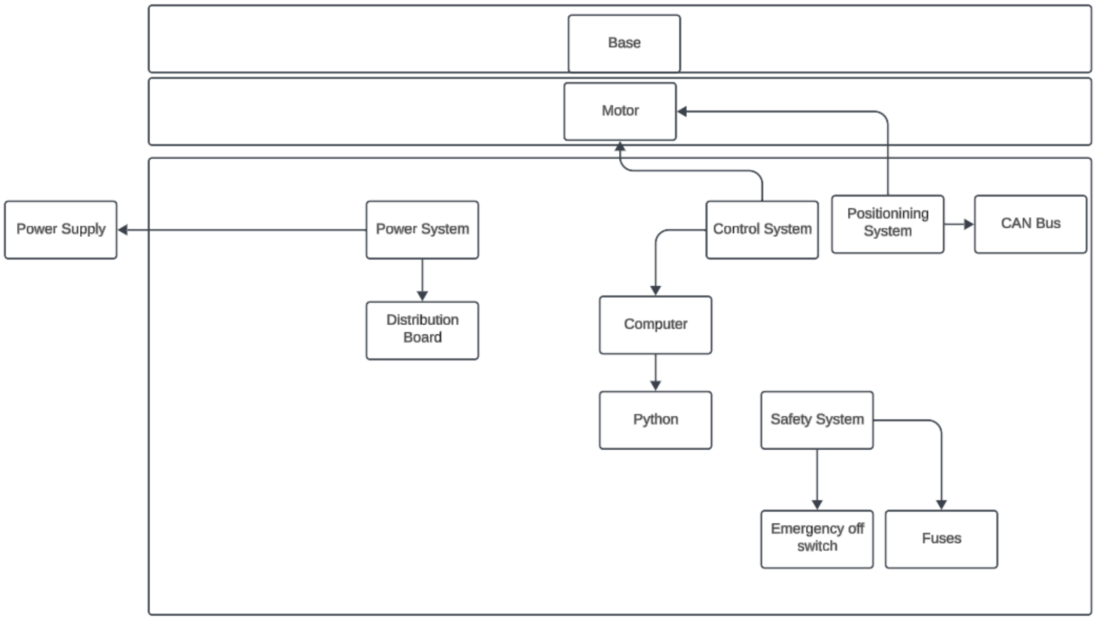


Figure 15: Product Architecture Geometric Diagram representing the robotic arm system modules interactions along with subfunctions.

In formulating the hierarchy of the subsystems, the Mounting System has the foremost position, symbolizing its role as the secure mount for the robotic arm as seen in **Figure 16**. The power system is situated within the space of the robotic arm, receiving electrical input from an external source (power supply), and distributing power among all motors using a distribution board. Similarly, the control system functions housed in the central region of the diagram functions as the controller for the robotic arm. The computer, serving as the microprocessor, governs electronic components for physical computing using Python. The positioning system, working in tandem with the control system, uses a CAN Bus to send the Python commands to each motor to position each motor at the correct location. The safety system features an emergency off switch and fuses on the robot to act as safety measures to keep the user safe from any failures or emergencies.

10.2 Definitive Layout

A near-complete design was created upon completion of the product architecture. The Human Robotic arm integrates mechanical design with important electrical design. The mechanical design will be discussed first, followed by the electrical information.

10.2.1 Mechanical Design

A detailed CAD of the team's proposed design is seen in **Figure 17**. The CAD model includes the base, aluminum extrusions, and all necessary joints to power the robotic arm. **Figure 18** is a side view of the Detailed CAD model, with arrows showing where each Degree of Freedom will act.

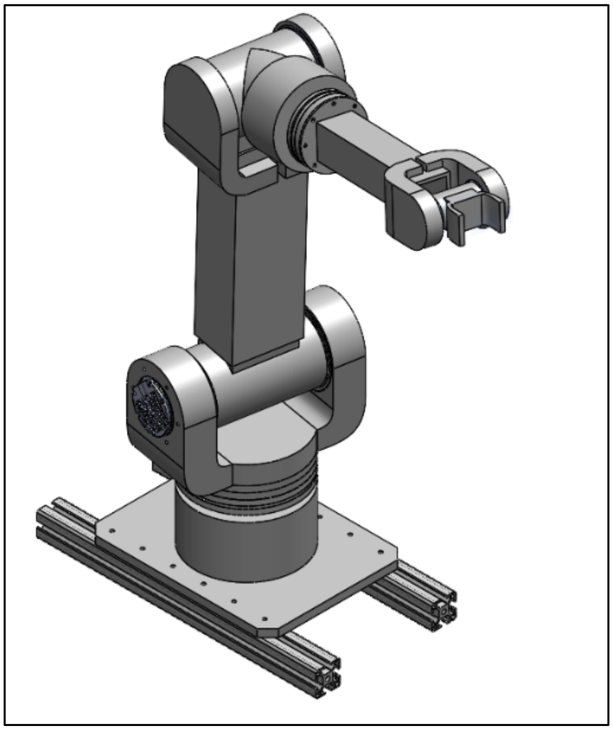


Figure 16: Detailed SolidWorks CAD assembly of structure and joints

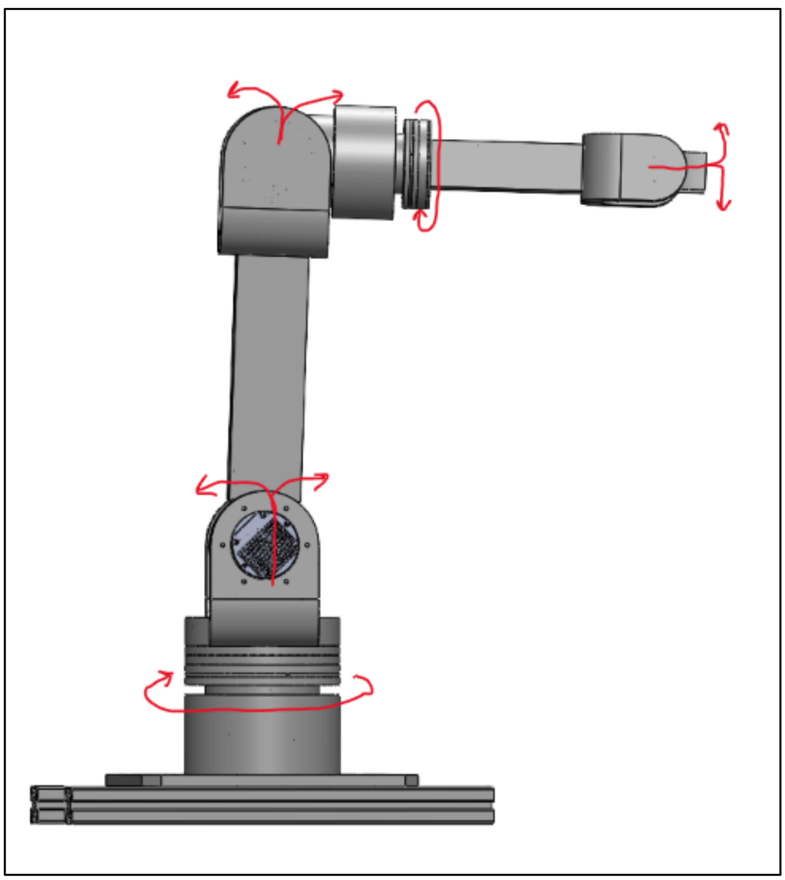


Figure 17: Side View Detailed SolidWorks CAD assembly of structure and joints

Figures 19, 20, and 21 are the CAD Models that CubeMars sent us when we asked representatives of the company. The CAD models of the motors were used to help us dimension the housing around the motors.

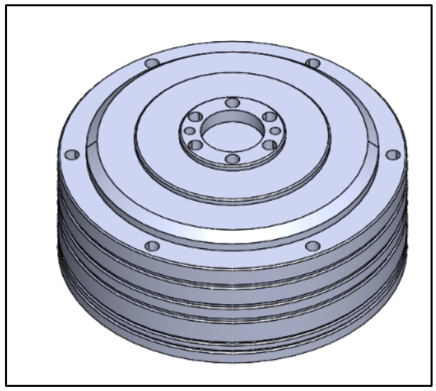


Figure 18: CubeMars AK10-9 Motor CAD Model

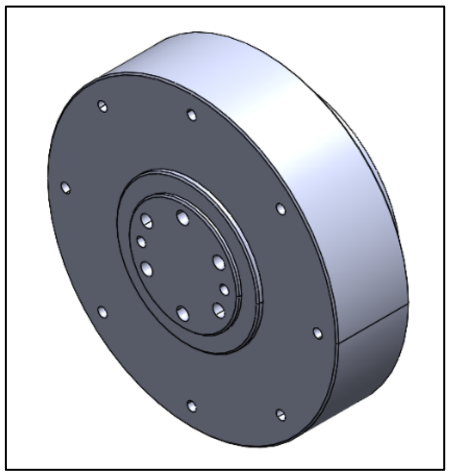


Figure 19:CubeMars AK80-6 Motor CAD Model

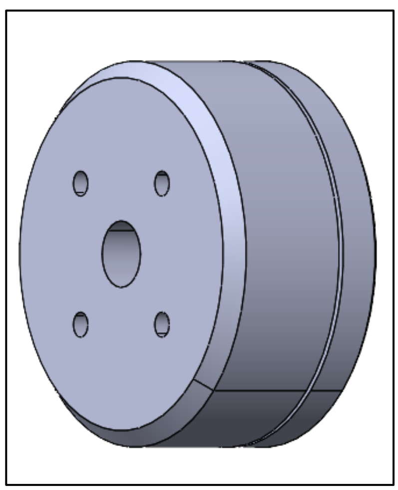


Figure 20: CubeMars GL40 Motor CAD Model

When designing and modeling the joint one motor housing, the team adopted a modular design to ensure repeatability and scalability for future joint designs. The team began by attributing a casing around the backside of the motor to secure it to the overall robotic arm manipulator base, as seen in **Figure 22**.

This casing would then encase a motor cap, with a cross-roller bearing sitting on top of it. The inner ring of the bearing was connected to the motor cap, while the outer edge was free to rotate. This was connected using a mushroom connection from the motor, located inside the motor cap, to the rotating base plate, which was also fastened to the outer ring of the roller bearing for free rotation. This setup allowed for 360° rotation at joint one.

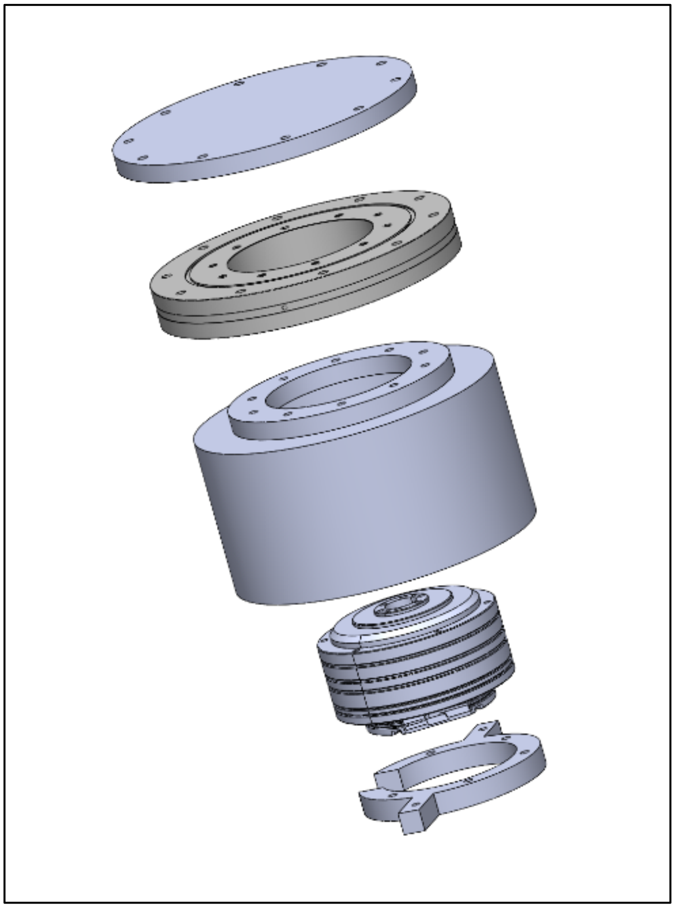


Figure 21: Exploded view of Joint 1 Assembly

Joint two is the first joint that would be hinging our robot forward and backward, rather than a rotational motion. Because of the amount of weight J2 supports, we wanted to reuse the same Brushless DC motor seen in Figure X and in joint one. The casing for the motor and bearing will be able to split in half for ease of assembly. The casing will be fastened to the top plate of J1. The cylinder for J2 will feature an extruded cut to allow us to fasten the cylinder into the motor. The extrusion on the right will be press fit into the bearing. The aluminum shaft has a cross-section of 3 x 4 inches and will be fastened onto the square extrusion. The aluminum shaft is one foot long and will be outsourced from McMaster-Carr. The exploded view of joint two can be seen in **Figure 23.**

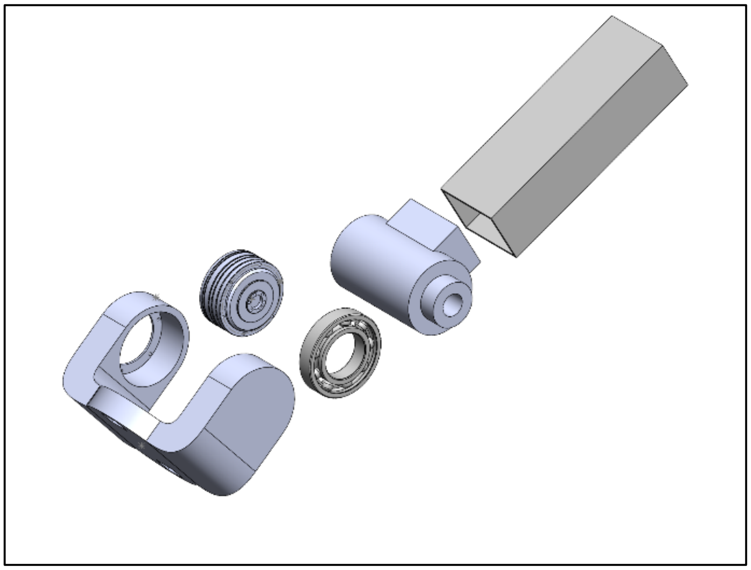


Figure 22: Exploded view of Joint 2 Assembly

The joint three Assembly in **Figure 24** is inspired by Joint Two's design. J3 features a smaller motor and also a smaller bearing. Using a similar cylinder design and an extruded cut, we will fasten the cylinder into the motor and press fit the cylinder into the bearing. J3 acts as the elbow of our assembly and the casings for the motor and bearing will be fastened into the aluminum shaft.

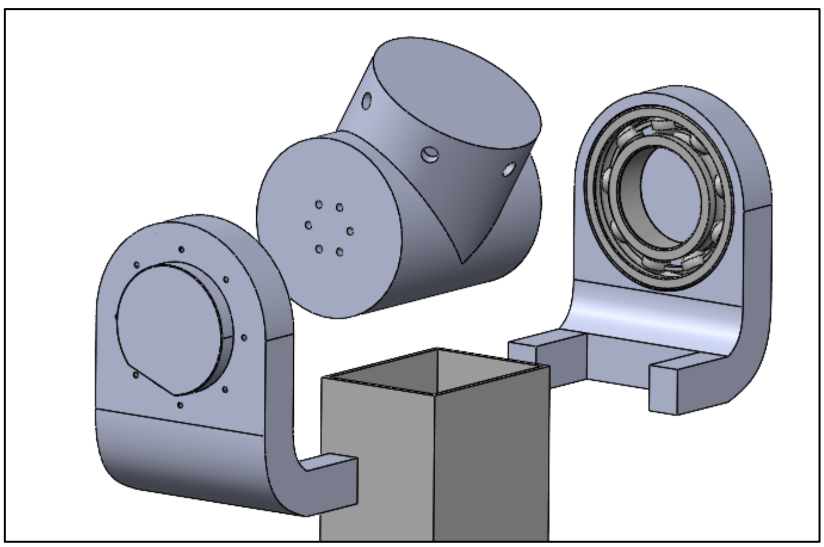


Figure 23: Exploded view of Joint 3 Assembly

Similar to J1's design, joint four features a very similar design to joint one. However, when designing J4 the team ran into a variety of manufacturing/assembly constraints that resulted in multiple iterations of the design. **Figure 25** features the cylinder seen in J3 with a casing on top to allow the motor to be fastened properly. Over the entire motor will be another casing that will be fastened to the bearing. The cap on top will allow the motor and bearing to move at the same time and provide enough torque to the forearm linkage.

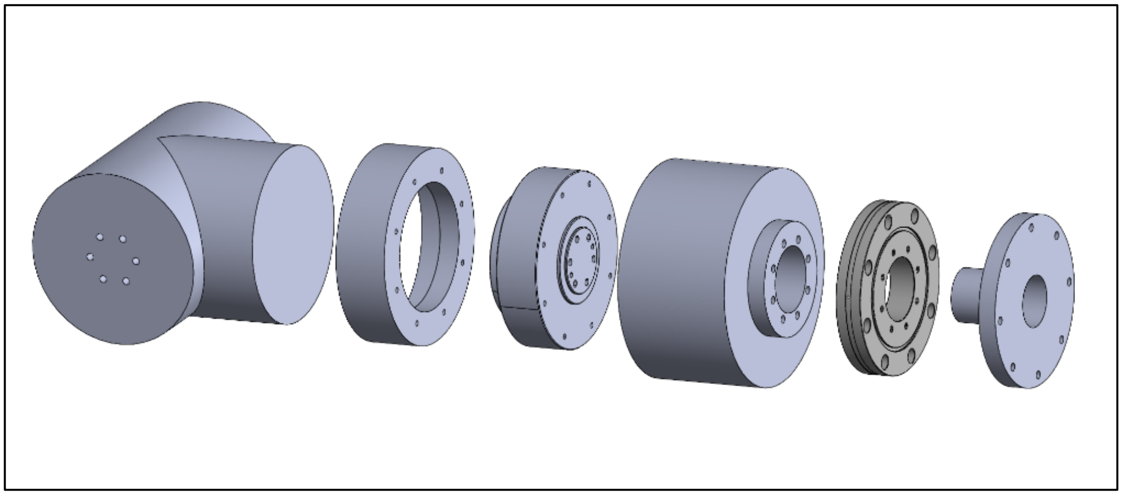


Figure 24: Exploded view of Joint 4 Assembly

Similar to J3's design, joint five features a casing for the smaller motor and bearing as seen in **Figure 26**. Due to the complicated hole pattern of the last motor, the cylindrical shaft had to be adjusted to feature a cap that would be fastened onto the cylinder. After fastening the cylinder to the motor, the cap can be fastened and then pressed to fit into the bearing. Joint five will allow up and down motion similar to a wrist.

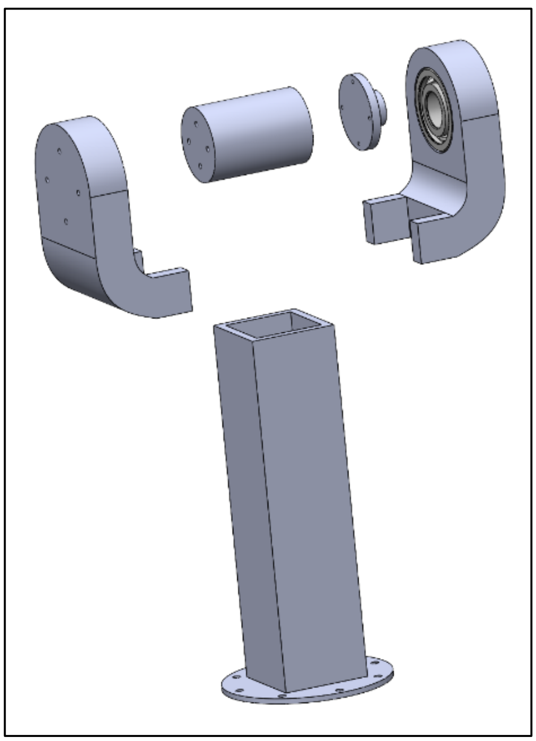


Figure 25: Exploded view of Joint 5 Assembly

10.2.2 Electrical Components

Our team has developed a setup for the robotic arm that integrates the necessary electronic components to ensure smooth operation. Each motor is equipped with an A1257WR-S-4P CAN connection, which allows us to daisy-chain the motors together. This chain then connects to a USB-to-CAN adapter, enabling communication with a computer where control scripts can be executed using Python. For power, each motor has an XT30PW-M port, and we use XT30-M to XT30-F adapters to connect these ports to a power distribution board. The board is wired directly to a power supply, creating a centralized and efficient way to manage power delivery across all the motors.

Looking ahead, we plan to enhance the system by adding fuses before each motor to protect against overcurrent and ensure no single motor receives too much power. This will help protect the motors and maintain the system's reliability. Additionally, we are working on incorporating an emergency switch for safety, allowing the entire system to be powered down quickly if needed. These improvements will make the robotic arm safe and dependable while ensuring it meets operational demands effectively. An illustration for each connection can be seen in **Figure 27.**

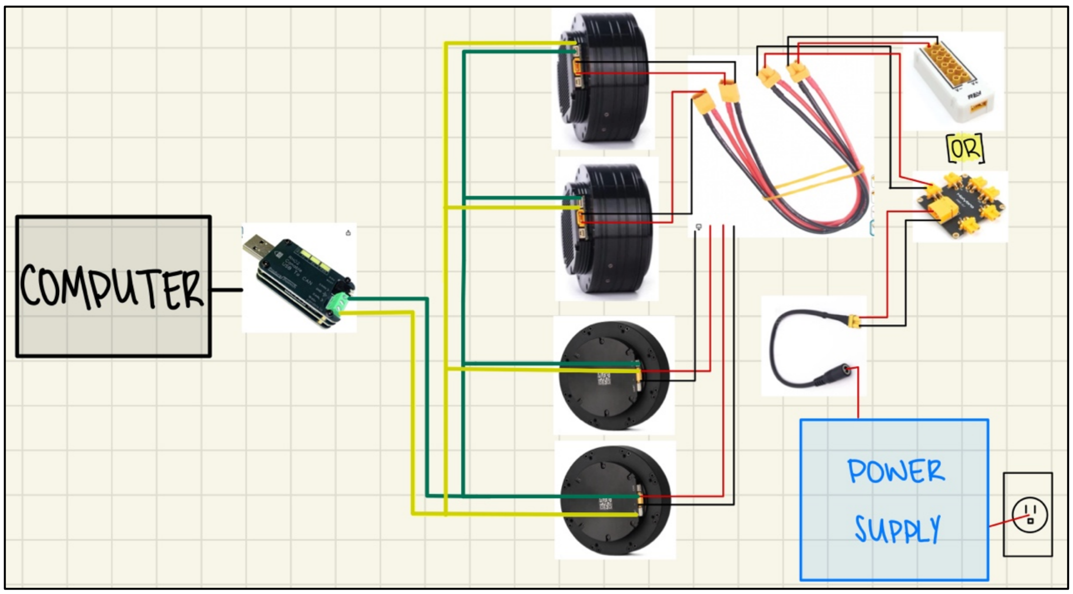


Figure 26: Power and CAN connection illustration.

10.3 Technical Analysis

10.3.a. Payload Verifications

To validate our design, the team needed to perform payload validation when the arm is undergoing maximum torque on the motors while in static equilibrium. To perform an accurate calculation for these two cases, the team identified the weight of all the cross-sections, as well as the motors and their allocated bearings. The distances from the center of mass of each of these components were calculated and verified using SolidWorks for further torque calculations. These calculations can be seen in **Tables 12** and **13.**

Table 12: Payload Analysis for J2 Max Length

Payload Analysis - J2 Max Length			
Type	**Weight (kg)**	**Length (mm) from J2**	**Overall Torque on J2 (Nm)**
A - aluminum 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 - AK80-6 KV100	0.485	525	774
J5 - GL40 KV70	0.107	807	
~~J6 - GL40 KV210~~	~~0.107~~	~~0~~	
B3	0.63	478	
B4	0.386	561	
B5	0.109	807	

Table 13: Payload Analysis for J3 Max Length

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 - AK80-6 KV100	0.485	47	12
J5 - GL40 KV70	0.107	329	**Mass Density (g/m^3)**
~~J6 - GL40 KV70~~	~~0.107~~	~~0~~	774
B4	0.386	83	
B5	0.109	329	

Tables 12 and **13** provided an accurate torque on the respected motor that was being analyzed when the robotic was at its static equilibrium edge cases for J2 and J3 extensions. From Table 12, we can see that the motor was experiencing a torque of about 21 Nm, with a maximum of 42 Nm. **Figure 28** shows the performance of this motor under these conditions.

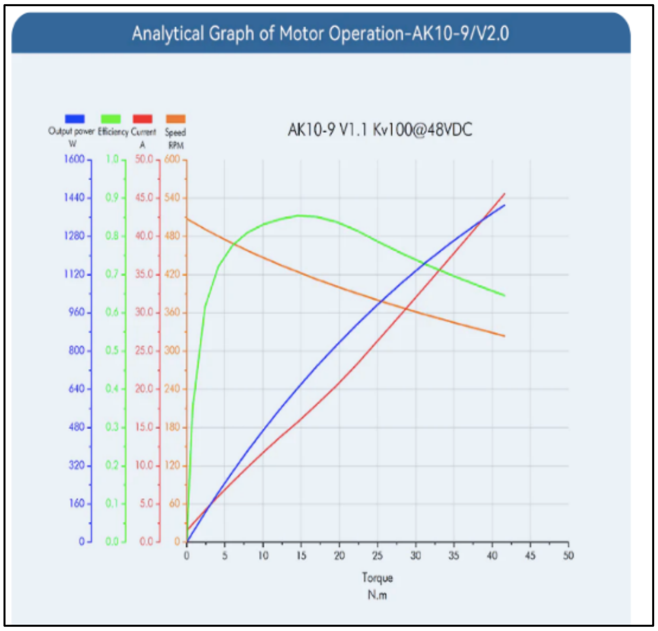


Figure 27: J2 Motor Criteria under Torque Load

As shown in **Figure 28**, the values for the AK10-9 motor were as follows: the motor current was 22 amps, the efficiency was 85%, the speed was 380 RPM, and the power was 880 watts. Furthermore, when the J3 was undergoing full extension, the team calculated a torque of approximately 4 Nm, while the maximum torque the J3 motor can handle is around 12 Nm.

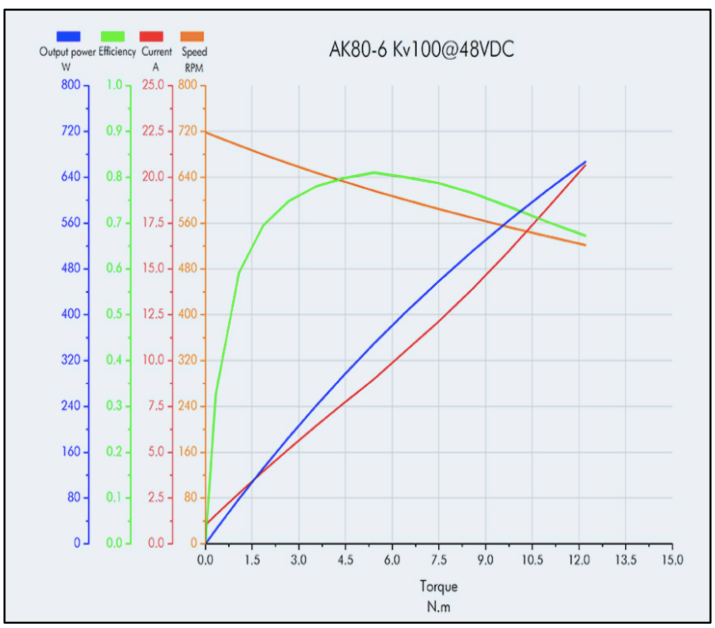


Figure 28: J3 Motor Criteria Under Torque Load

As shown in **Figure 29,** the values for the J3 AK80-6 motor under a 4 Nm torque load were as follows: the motor current was 6 amps, the efficiency was 78%, the speed was 650 RPM, and the power was 240 watts. These values helped verify that when the arm is at full extension, it will not tip or cause the motors to become over-torqued. This also helped the team identify the amount of current needed for the motors to achieve the desired torque output.

10.3.b. Material Testing and Validation

10.3.b.i PLA Tensile Test – ASTM D638 Type 1

The team decided to perform a Tensile Test According to ASTM D638 Type I to provide the required tensile strength value and other mechanical properties for simulation. The team fabricated the dog-bone-shaped specimen with dimensions according to standard specifications seen in **Figure 30**. For 3D-printed PLA, the team kept the print layers oriented in a consistent direction throughout all specimens. The width, thickness, and gauge length were measured with a digital caliper, following the ASTM D638 requirement. The measurements taken at the center and within 5 mm of each end in the gauge length were measured in order to be as accurate as possible.

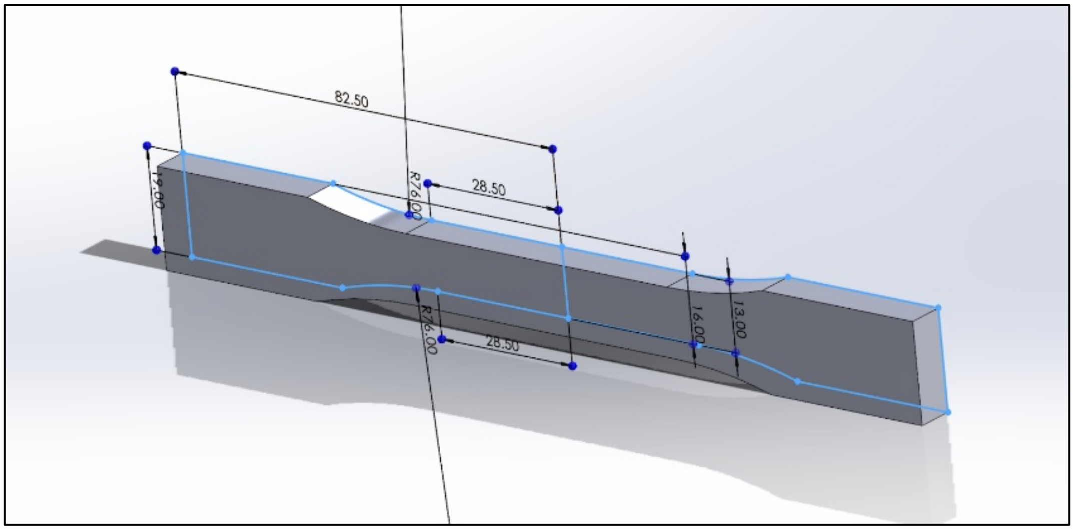


Figure 29: Tensile Test ASTM Standard Dog Bone

The testing machine was calibrated and set up for the test and fitted with the appropriate load capacity and an extensometer for the elongation measurement. A test speed of 5 mm/min was decided upon, considering the material rigidity of PLA, as stated in ASTM D638 Table 1. The team placed the specimen carefully in the testing machine and made sure that the load axis coincided with the specimen to avoid bending the specimen. A Class B-2 extensometer was used for modulus determination, measuring the elongation during the test correctly.

The tensile property analysis that followed after the completion included the determination of the ultimate tensile strength, estimated from the maximum load applied using the original cross-sectional area of the test specimen, and elastic modulus determined from the slope in the stress-strain graph of the tested material. Further to these, elongation at break calculated indicated the ductility of the materials tested. Observations of fracture behavior, including whether the failure mode was ductile or brittle, were noted for future analysis.

10.3.b.ii PLA Flexural Testing - ASTM D790 Type I

The preparation of specimens for flexural testing was done in the form of a rectangular bar, whose dimensions met the requirements of ASTM D790-17 seen in **Figure 31**. The length of the specimens was 128 mm, based on 8 mm thickness, and the width was 12.7 mm. These dimensions are selected so that the tests represent the most common flexural conditions of PLA material. The span between supports is calculated as 16 times the thickness, which gives 128 mm, and is verified for satisfying the requirements of this setup within 1% or better accuracy.

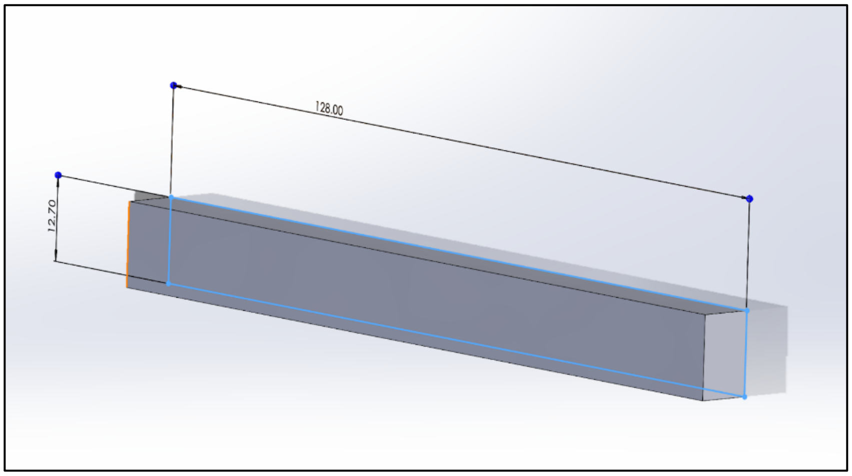


Figure 30: PLA Beam for Flexural ASTM Standard Test

The testing setup involved aligning the specimen on the supports, ensuring that the long axis of the specimen was perpendicular to the loading nose. The test was conducted with the crosshead motion rate set in accordance with ASTM D790, which ensured proper load application through the loading nose. The deflection was measured accurately using a deflection gauge. Continuous data was acquired to plot the load-deflection curve, which is important for determining flexural strength and modulus.

10.3.b.iii Experimental Results for PLA Material Testing

Both tensile and flexural tests were important in determining the material properties of the experimental PLA that will be used for Robotic Manipulation components, which was printed at 40% infill with a default infill structure. These tests yielded data that will enable the team to assess the mechanical performance of the PLA material under realistic loading conditions. Elastic Modulus measured in 1367.00 MPa describes the rigidity of the material whenever stress is applied. The mass density of PLA is 773.32 kg/m^3, accounting for compactness and overall weight characteristics.

During the tensile tests, Tensile Strength was figured at 11,426,304.65 N/m^2 (or Pa), yielding an interpretation of the number that defines how the material reacts against tensile forces until its failure. Additionally, the calculated Yield Strength was 14.80 MPa, representing the stress at which the material begins to deform plastically and permanently. These material properties were critical for evaluating the PLA's suitability for the robotic arm application through FEA and ensured that the material would perform reliably under expected load conditions.

10.3.c. Finite Element Analysis and Verification

In order to determine the validity of the design, the team needed to perform finite element analysis on the design. Conducting finite element analysis ensures the design is both functional and reliable. It ensures that the arm can handle the forces exerted during tasks, maintain precision under dynamic loads, and achieve a balance between weight and strength. The team chose to conduct FEA through SolidWorks. The first step in FEA was to recreate the 3-point-test and validate simulation results with experimental results. 40% infill was recreated in the model to match the 3D printed part. The boundary conditions were set to match the experimental set up. This includes constraints 10 mm from the edge of each side and a line force in the middle of the part. A line was chosen because in the experiment a rounded surface was applying pressure to the specimen and a line is the intersection of a rounded surface and a flat surface. **Figure 32** below displays the boundary conditions.

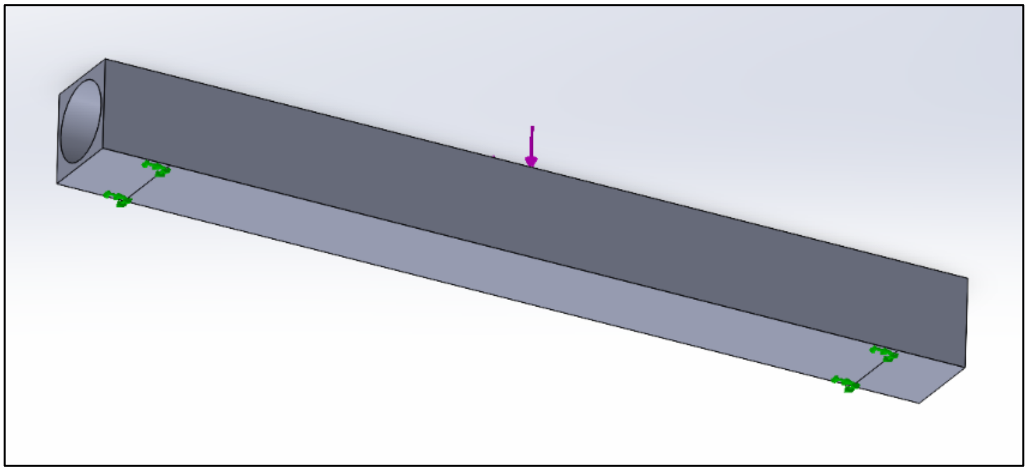
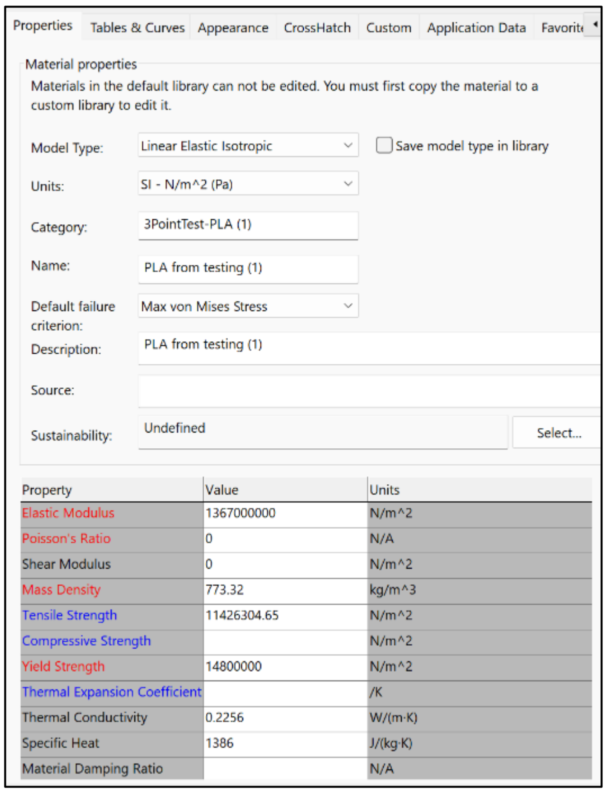


Figure 31: FEA boundary conditions

Once the boundary conditions were established, the next step in the FEA process was to input the material properties. These properties were determined from material experimentation (**Figure 33**):



Properties | Tables & Curves | Appearance | CrossHatch | Custom | Application Data | Favorite

Material properties

Materials in the default library can not be edited. You must first copy the material to a custom library to edit it.

Model Type: Linear Elastic Isotropic — Save model type in library

Units: SI - N/m^2 (Pa)

Category: 3PointTest-PLA (1)

Name: PLA from testing (1)

Default failure criterion: Max von Mises Stress

Description: PLA from testing (1)

Source:

Sustainability: Undefined — Select...

Property	Value	Units
Elastic Modulus	1367000000	N/m^2
Poisson's Ratio	0	N/A
Shear Modulus	0	N/m^2
Mass Density	773.32	kg/m^3
Tensile Strength	11426304.65	N/m^2
Compressive Strength		N/m^2
Yield Strength	14800000	N/m^2
Thermal Expansion Coefficient		/K
Thermal Conductivity	0.2256	W/(m·K)
Specific Heat	1386	J/(kg·K)
Material Damping Ratio		N/A

Figure 32: FEA material properties

Finally, a force of 118 N was applied to the specimen and the simulation was conducted. 118 N of force was chosen because this is the force that the experimental specimen broke at. Below are the results of the simulation:

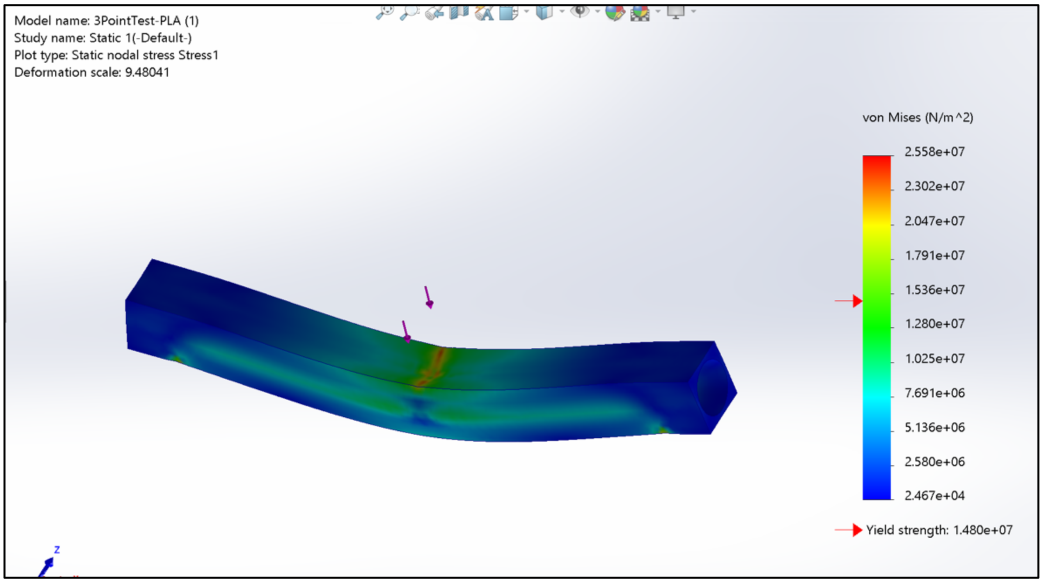


Figure 33: von Mises results from FEA simulation

The simulation results matched the experimental results as seen in **Figure 34**. The yield strength was surpassed when a force of 118 N was applied resulting in plastic deformation in the specimen. These results match the experimental results which also resulted in plastic deformation when a force of 118 N was applied.

10.4 Preliminary Product Risk Analysis

Throughout the design phase of the human robotic arm attachment project, the team was aware of several product failures that may occur through manufacturing and operation. These potential failures were documented using a Failure Mode, Effects, and Criticality Analysis (FMECA) and a Fault Tree Analysis (FTA) in order to assess each failure with its potential causes and effects. The FMECA is a structured approach to identifying potential failure modes in a system, assessing their effects, and prioritizing their criticality to guide risk mitigation efforts. Seven different failure modes were assessed and recorded as seen in **Table 14.** To complete FMECA tables, the team began by listing all potential failure modes for each component of the system, along with their possible causes and effects on the overall functionality. Next, a severity rating was assigned to each failure mode to assess its impact on the system. Then, the likelihood of occurrence for each failure and the ease of detection were each evaluated to calculate the Risk Priority Number (RPN) or criticality rating. These ratings were then used to identify the highest-risk failure modes that require immediate attention. Finally, mitigation strategies or corrective actions were proposed to reduce the likelihood, severity, or undetectability of these failures and improve system reliability. The highest critical product failures that were identified included overuse/burnout of joint motors and failure to move/incorrect movement of actuators. These were identified to have the highest concern because they resulted in the highest RPN value.

Table 14: FMECA Table used to organize causes, effects, and solutions strategies for high priority product failures for the Human Robotic Arm Attachment.

Part and Function	Potential Failure Mode	Potential Effects of Failure	Severity	Potential Causes and Mechanism of Failure	Occurrence	Current Design Control Test	Detection	Recommended Action	RPN
Actuators (Joint Motors)	Failure to move or incorrect movement	Inability to position the arm correctly, leading to task failure or collision	9	Motor wear, overload, overheating, power supply issue, seizing	4	Periodic motor inspection	3	Upgrade motor rating, add overload protection	108
Control System (Software)	Failure in control algorithm	Inaccurate control, potential for oscillations, lack of stability	8	Software bug, incorrect control tuning, signal noise	2	Code reviews, simulation testing	3	Improve controller tuning, add redundancy checks	48
Arm Structure (Links)	Structural failure or deformation	Misalignment in movements, excessive vibration	10	Material fatigue, impact load, stress concentration	2	Stress analysis during design, load testing	2	Use stronger materials, inspect regularly	40
Encoders (Position Feedback)	Loss of position feedback	Loss of position control, leading to inaccurate movements and potential collisions	8	Sensor failure, electrical noise, misalignment	3	Regular calibration, signal filtering	3	Use higher-quality encoders, improve shielding	72
Joint Motors	Overuse/Burnout	Motor overheating, reduced lifespan, loss of functionality	8	Continuous use, Continuous high load operation, Lack of Cooling	6	Thermal sensor monitoring, maintenance checks	3	Implement time usage limits and torque limits.	144
Electrical Failure	Failure to power motors	Loss of movement in the arm, burning out motor	9	improper wiring, wrong power source, over use of motors	3	checking each individual motor, voltage testing across wires	3	Implement wire testing, implement safety on voltage	81
Structural Components	Fastener Loosening/Thread Stripping	Components loosening/falling out of place/robot becoming unstabilized	8	Excessive vibration/parts not moving cohesively together/moving against each other	5	Testing each motor individually/confirming all connectors are secure with proper inserts	2	Ensure that each insert is of proper size and screws are rated for high vibrations	80

The second kind of documentation that was used to assess the product failure was a Failure Tree Analysis (FTA). An FTA is a top-down, deductive failure analysis technique used to identify the root causes of a system failure or undesirable event. Within the diagram, the rectangles represent intermediate or top-level events caused by the interaction of underlying factors, while circles denote basic events, which are primary root causes that do not decompose further. The circles feed into rectangles via logical gates (e.g., AND, OR), illustrating how individual failures combine to create system-level issues. The team completed an FTA analysis of when the robotic arm fails to complete a task since this was seen as a high risk on the FMECA table. Three intermediate events were identified including software failure, structural failure, or actuator failure. Potential causes for software failure include control algorithm error, loss of data, or input out of range. Potential cause for structural failure could include material fails and/or snaps or fastener failure. Lastly, the potential causes for actuator failure could include motor overload, power supply interruption, or complete motor failure. All components were organized in a diagram as seen in **Figure 35.**

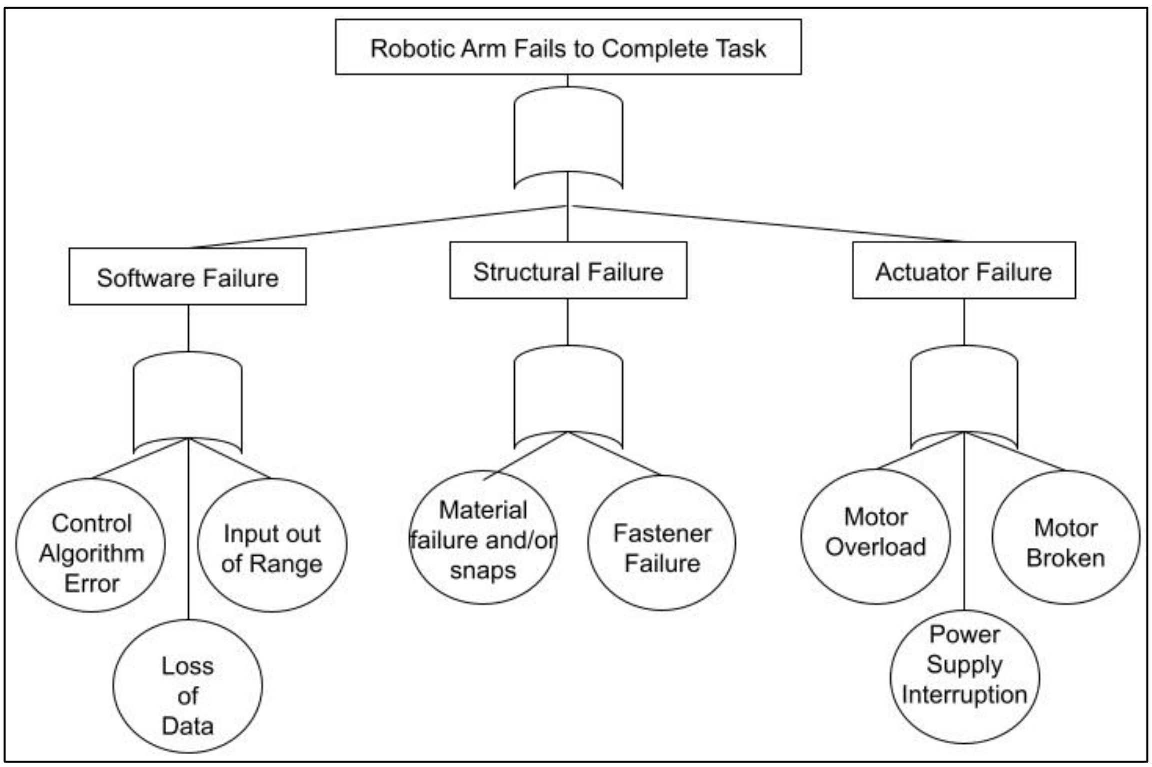


Figure 34: Robotic Arm Failure FTA Diagram.

11. Validation Plan for MEEN 402

The validation plan ensures the robotic arm prototype fulfills predefined requirements for its functionality, structural integrity, and system performance. The robotic arm validation consists of breaking up the validation into sub-validations focusing on specific sub-systems, including structural integrity, joint functionality, motor validation, and multi-motor system integration.

The most crucial validation for the robotic arm prototype involves ensuring the system can operate effectively with all degrees of freedom (DoFs) functioning in unison. The process begins with validating one motor and its associated DoF. If the motor operates as expected, additional motors and their corresponding DoFs will be incrementally integrated into the system. Each step will be assessed qualitatively with a "yes" or "no" depending on whether the solution meets predefined performance criteria. Success requires the validation of all sub-systems, making this the primary validation goal.

The structural validation goal is to confirm that the robotic arm has sufficient structural integrity to handle operational loads without collapsing or deforming. FEA simulations will be performed to assess the stresses and strains on the arm under various load conditions. The locations will include all of the linkages, the rotating J1 base, and the end-effector of the robot. This analysis will provide quantitative results to validate the design's robustness. Material selection, particularly for the arm's critical points, will be optimized through these simulations. Further physical testing will be conducted to correlate theoretical results with real-world performance, ensuring consistency between simulation and reality.

The joint validation process ensures all joints are free from obstruction and capable of smooth articulation. A detailed inspection of the assembled arm will identify potential issues such as misalignments or interference that could impede performance. Each joint will undergo testing to confirm that it allows unrestricted movement through its designed range of motion.

The motor validation process begins with small translational and rotational movements to verify the alignment between motor inputs and the corresponding output motions. Initial testing will focus on basic, isolated movements to refine controls and ensure accurate performance. These movements will confirm that the motors respond correctly to inputs and are capable of executing programmed commands.

After validating individual motors, the system will progress to multi-motor integration. Testing will begin with simple coordinated movements involving two motors and gradually expand to more complex motions with all motors working in unison. The validation aims to ensure synchronization between motors and the seamless execution of complex tasks. Any issues with calibration, response time, or motor interference will be addressed during this phase.

By systematically validating each sub-system and integrating them into the larger design, the robotic arm prototype will meet performance expectations, paving the way for successful deployment.

12. Budget Planning

12.1 Bill of Materials

The bill of materials, also recognized as the BOM, is able to document all expected spending for the Human Robotic Arm Project throughout the semesters of MEEN 401 and 402. The budget was given to the team by Los Alamos National Laboratory and the Mechanical Engineering Department with a total of $5,000. As of now, the total amount used for allocated parts totaled $3,942.79. This gives the team of up to $1,000 for any additional costs due to reordered components or additional components needed for design changes. The bulk of the money spent was used for the motors and bearings used within the design, motors totaling close to $2,800 with the bearings attached totaling close to $900. The remainder of the money was spent on the electronic components and the fasteners used to attach all parts to the 3D printed housing. The power supply needed to power the motors is planned to be provided by Los Alamos National Laboratory since purchasing this would be a large chunk of our budget. The team is also planning to print all the housing using the 3D printers and filament provided at Texas A&M with already allocated spending given to each capstone team.

Overall, the BOM was able to give the team a good idea of the amount of money spent on each component as well as give an idea of how much money can be spent on repairs or money spent to optimize for better material. The team plans to edit and solidify the BOM over winter break to reflect the exact number of fasteners and the exact length of wires needed throughout the final design. The most up to date BOM can be seen in **Appendix I.**

13. Scheduling and Project Management

Within MEEN 401 and 402, project planning and management are major components that can contribute to successfully completing the project. Efficient and effective planning enables the team to track progress and assign tasks and time for certain milestones throughout the project. It is also important to plan to identify the critical path for the project. Identifying this path allows for effective planning since the critical path is the sequence of the tasks that require the most time to complete. Among this, the team can then quantify the risks related to each task and continually optimize their plan. The tools learned within MEEN 401 to help plan and manage include a Work Breakdown Structure (WBS), a Task Dependency Diagram (TDD), and a Gantt Chart. The following subsections contribute to each of these tools and how they were used within the project.

13.1 Work Breakdown Structure

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 36**. The overall outline of the structure was directly related to the MEEN 401 lecture schedule defined through writing assignments and milestones presented at the beginning of the semester. The WBS for MEEN 402 will be based directly on each team's plan to complete the project.

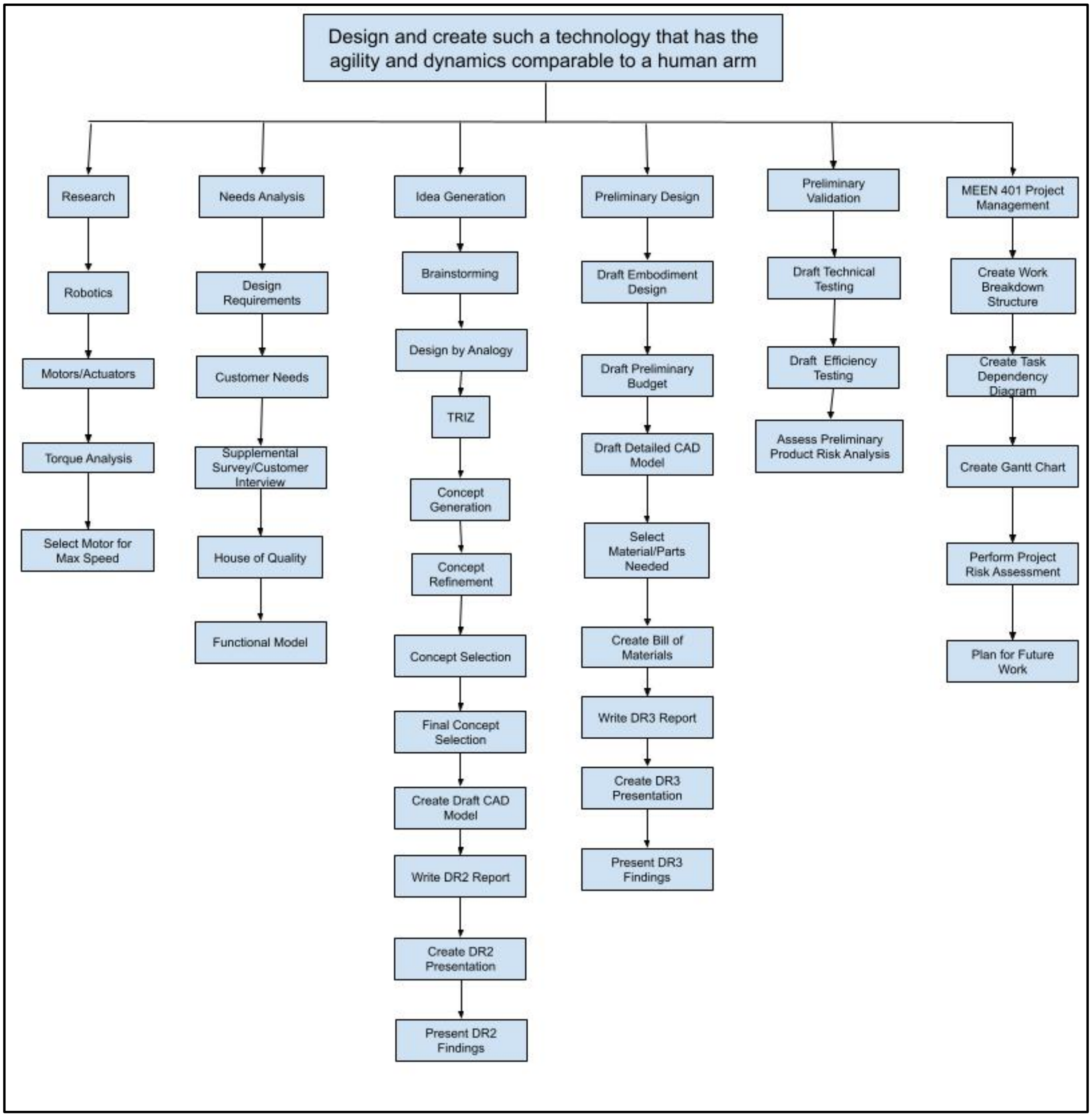


Figure 35: The WBS for the Robotic Arm Project.

13.2 Task Dependency Diagram

A Task Dependency Diagram (TDD) is a directed graph indicating the required sequencing among a set of tasks. It is a way to visualize the specific order of tasks that need to be taken to reach the completion of the project. The remainder of MEEN 401 for the Robotic Arm Project was put into a TDD as seen in **Figure 37**. The tasks in the TDD are arranged in a specific order because each task must be completed before the subsequent one can begin. Creating the TDD was able to allow the team to find the critical path, which is defined as the sequence of steps that require the longest time to complete. Although the critical path tasks must be completed in a strict order, the tasks outside the critical path are still important but can be done in any order without delaying the project, giving more flexibility. However, if any task on the critical path is delayed, it will push back the entire project. The critical path is defined in red as seen in **Figure 37** while all other tasks are shown outside of this path.

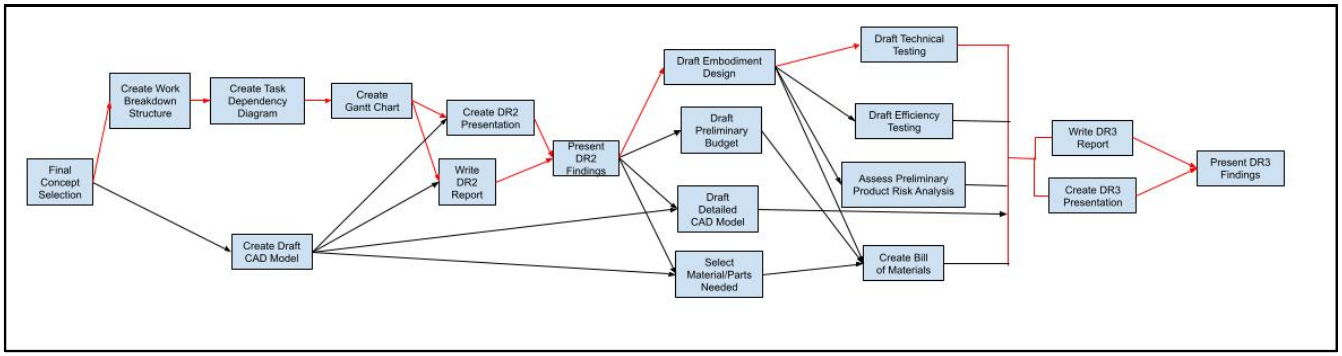


Figure 36: Task Dependency Diagram for Robotic Arm Project.

13.3 Gantt Chart

The last tool presented in MEEN 401 within project management 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. The critical path is also included to keep the team up to date on the progress made along the critical path. 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 expected schedule for the rest of the semester is shown in **Figure 38.** The color components of the chart can represent which person or persons are responsible for the task along with the tasks that follow the critical path. The availability for the team is also included on the chart including dates of holidays and personal unavailability due to other commitments.

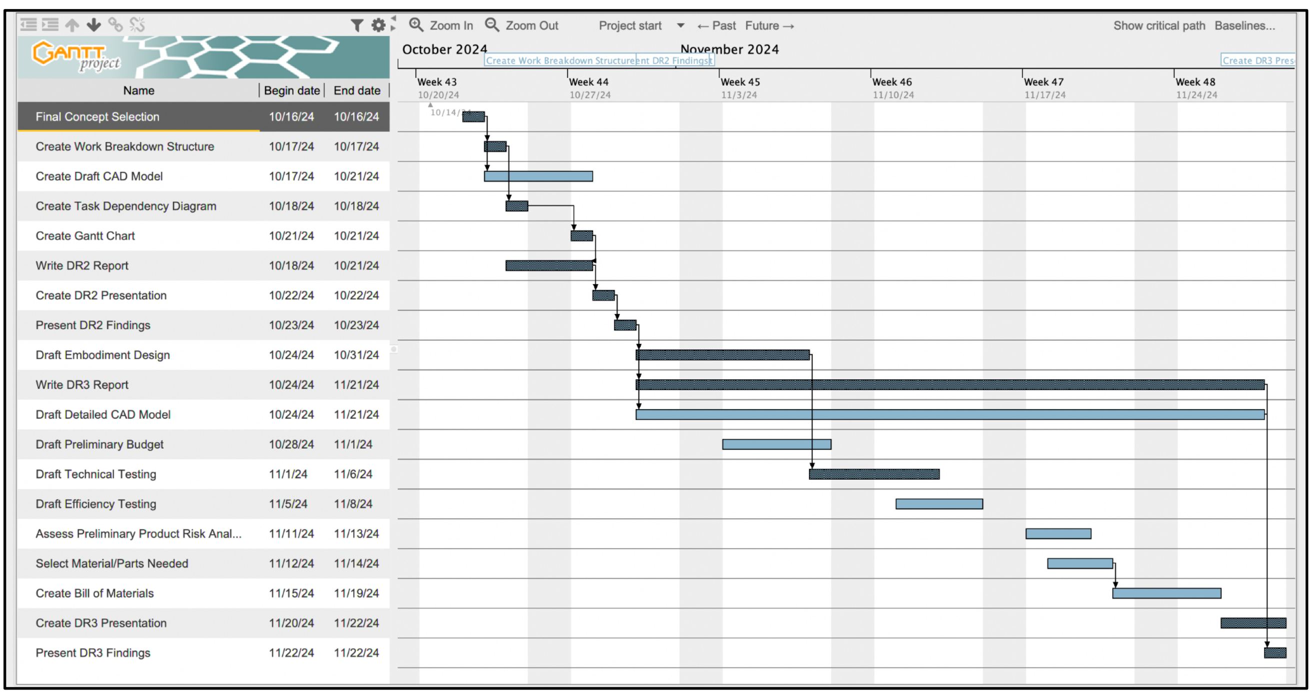


Figure 37: Gantt Chart for Fall 2024.

The following Gantt Chart seen in **Figure 39** shows the predicted schedule for next semester in MEEN 402. This Gantt Chart shows the weekly task that need to be completed in order to stay on schedule to finish by the end of March. The major milestones include 2 weeks of printing 3D printed parts, incorporating electrical components, integrating software, and 4 weeks of testing and calibration. The team decided to plan to finish by the end of March to allow the team 6 weeks of cushion time before final showcase. The was also 4 additional Gantt Charts created to show individual tasks for each team member throughout the semester as well as a Holiday Break Gantt Chart for tasks completed over break and can be found in **Appendix G**.

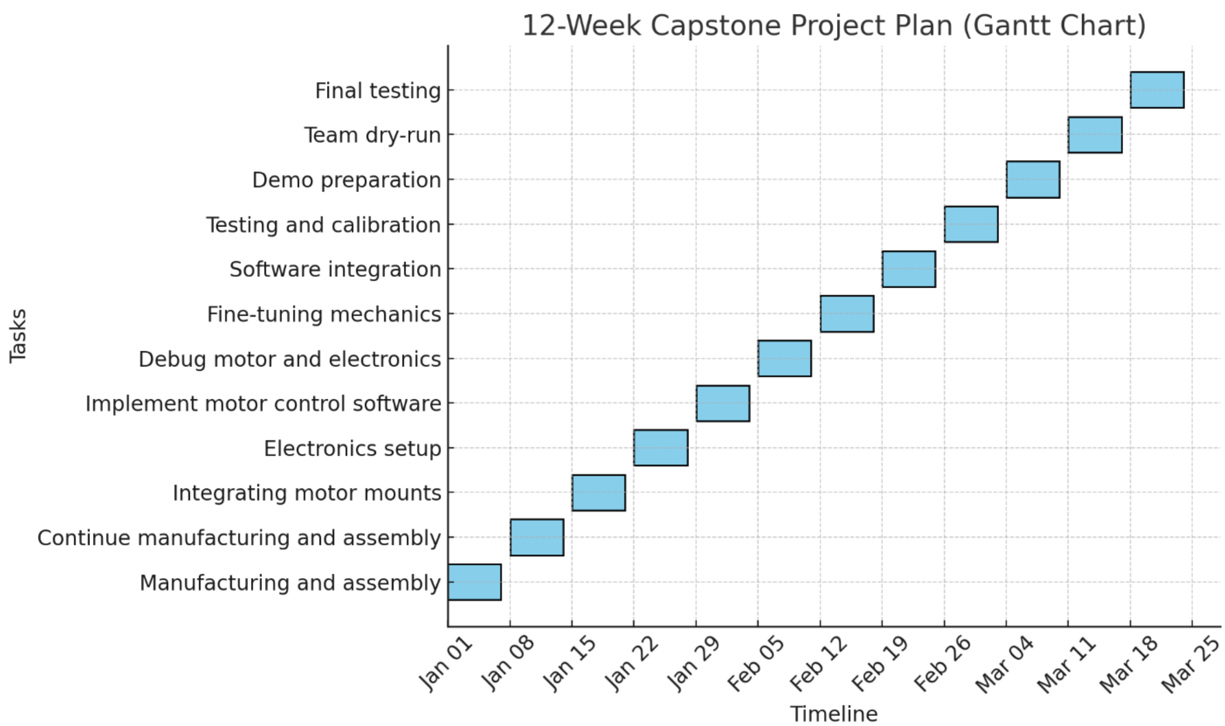
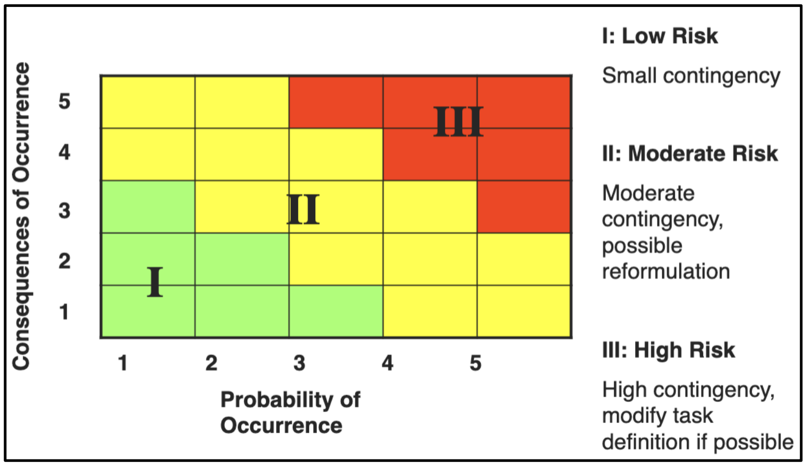


Figure 38: Gantt Chart for MEEN 402 Semester.

13.4 Process Risk Assessment

To continue the project scheduling process, a risk assessment was performed for the MEEN 401 design process as detailed in **Figure 40**. A thorough completion of this analysis allows for the team to complete the project with the identification of risks to aid the team through events that could have negative effects on their task timeline. Each task was evaluated by the team to identify risks that could be of concern and the template can be seen in **Table 15.** Through the identification of risks, a rating system was used as seen at the bottom of the table to evaluate the probability and consequence of the occurrence of the risk seen on the x and y axis. In evaluating the probability and the resulting consequence, a plot can be made to evaluate where the risk falls on the rating scale. The corresponding color, either red, yellow, or green, reflects the level of risk as either high, moderate, or low.

Table 15: Risk Assessment Table



In identifying the risks and rating them, the highest risk that was identified within the remaining MEEN 401 deliverables was during the task of drafting the preliminary budget. The risk included part price changes and stock availability. The team ranks the probability as a 3 and the consequence of occurrence as a 4. The main objective for this rank was due to the specific motors that the team is planning to use and the performance of it. The tactic that is planned to be used is to draft multiple sources for the same part so that the team has a range to order from. The table for these risks can be seen in **Figure 40**. The remaining risk assessment tables can be seen in **Appendix G**.

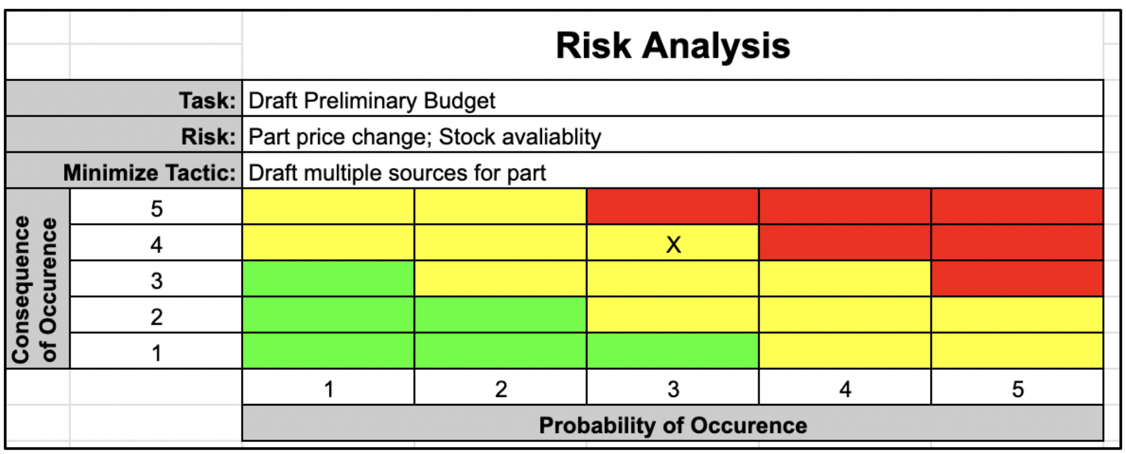


Figure 39: Risk Analysis for Part Price Changes/Stock Availability.

Additionally, the team conducted a process risk assessment for items within the MEEN 402 semester. The highest risk that the team found was the task of motor torque overloading. This means that the torque applied to the motor is past its accounted limit which could cause the motor to break. The risk that this causes is making the motor seize and potentially a full breakdown. This would then result in the team having to purchase an entire new motor which is not accounted for in the budget. The probability that this could occur was rated at a 4 (High Risk) because this is the first time the team has used these motors and put them into application. The team also rated the consequence as a 5 (Extreme) because it would result in the team having to purchase new motors which would be very expensive. The mitigation techniques that the team thought of is to ensure that all hand calculations are thoroughly analyzed and checked by experts. With this, it will allow the team to confidently follow their plan with accurate load calculations. The team is also planning to build and test each motor individually, strategically increasing the number of motors and ensuring no problems occur.

		Risk Analysis				
Task:		Motor Torque Overloading				
Risk:		Results in motors seizing/breaking the function of the motor				
Minimize Tactic:		Provide hand calculations with the torque output; Modular motor testing				
Consequence of Occurence	5				X	
	4					
	3					
	2					
	1					
		1	2	3	4	5
		Probability of Occurence				

Figure 40: Risk Analysis for Motor Torque Overloading.

14. Final Deliverables

The team has outlined the final deliverables expected after both MEEN 401 in December 2024 and MEEN 402 in April 2025. By the end of MEEN 401, the team is expected to produce a detailed CAD model of the robotic arm. This model will provide a clear visual representation of the anticipated final product and enable the team to conduct various validation techniques to ensure the design's success. These techniques include performing static and dynamic analyses, such as finite element analysis (FEA). Additionally, the team will develop a validation plan to test the mechanical capabilities of the prototype to be built during MEEN 402. A preliminary budget and bill of materials will also be prepared, allowing the team to account for shipping timelines and costs.

The deliverables for MEEN 402, to be completed by April 2025, include the creation of a functional prototype that demonstrates the key features developed in collaboration with the sponsor, Los Alamos National Laboratory. The prototype will undergo optimization efforts, including mechanical testing and efficiency analysis. All findings will be documented in a report, allowing the team to present the results to the sponsor or future project teams. A user manual will be developed to guide future users in controlling the arm, along with templates of the code used to operate it. Lastly, a comprehensive final report will be compiled, summarizing the team's work and facilitating future improvements to the design by future teams.

15. Future Work

To progress toward the completion of our human robotic arm project, several critical tasks have been identified for the next weeks. First, all necessary materials and components for prototyping must be ordered to facilitate assembly and testing when returning from the break. This includes submitting all part orders through the Mechanical Engineering Department and confirming all orders placed. Concurrently, research and evaluation of circuit designs, electronics, and power supply options will be conducted to ensure optimal performance and reliability. Understanding motor functionality will be a key focus, involving hands-on experimentation and implementing python test scripts to evaluate motor maneuverability. On the design side, fasteners will be incorporated into the CAD model to enhance the structural integrity of the assembly. Furthermore, finite element analysis (FEA) will be performed on critical components to assess and mitigate potential failure points, ensuring the design can withstand expected loads. These task will form the foundation for refining the prototype and moving closer to achieving the project objectives.

16. Conclusions

The challenges present at The Hanford Site demand a solution that can overcome the complexities during the process of removing solidified radioactive waste from underground tanks. The additional challenge that parallels with this issue is having an environment of a confined and highly radioactive space. This capstone project, in collaboration with Los Alamos National Laboratory (LANL) and the team from Texas A&M, aims to provide a solution by designing of a 6-Degree-of-Freedom Human-like robotic arm attachment for a Quadruped Spot Robot. By developing this solution, the team's goal is to reduce environmental and safety risks associated with hazardous waste cleanup. In the intent to resemble human-like mobility and operational speed, the robotic arm will be able to access and manage waste in hard-to-reach areas in the tanks, which would be out of reach using traditional methods.

With this scope defined, the team collected design requirements through the use of the House of Quality method. This allowed the team to align customer needs with functional requirements. In developing the arm's functionality, a Functional Model was created to outline the operations that the Human Robotic Arm would perform. Additionally, the team began the idea generation process by using three methods; Brainstorming, Design-by-Analogy, and the TRIZ method. Collectively, the team organized all their ideas into a morphological matrix to begin concept refinement. Four coherent concepts, combining design components from the matrix, were made and compared. Through using two concept selection methods, a Pugh Chart and a QDTESM matrix, the team was able to choose one concept based on the original customer needs and functional requirements. The final design concept that was chosen was Concept 4 with the components of 6 motors following 6 DoFs, PLA 3-D printed housing, and a telescoping arm. The next deliverables in MEEN 401 included the embodiment design for the selected concept which was comprised of a highly detailed CAD design, incorporating all DoFs with an assembly of all motors and bearings. A bill of materials was also developed along with a validation plan that will be performed in MEEN 402. Following these future plans, a successful design with a complete and functional prototype will be attained by the end of April 2025 through the completion of MEEN 402.

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Appendix

Appendix A: Complete Technical Questions

Table 16: A-1 Justification for the Problem Statement and Mission Statement.

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

Appendix B: Customer Needs Interview Form

Table 17: B-1 The Customer Needs Interview form organized questions and customer responses from each interview. The form helped extract the team's needs and their associated weights for analysis.

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

What specific motions would you expect the robot /robotic arm to handle regularly? (Movement, force)	The robot should be capable of moving back and forth over a specific area during cleaning operations.	The robot needs to perform sweeping motions and accurately identify the edges of curved surfaces on the wall, requiring mathematical precision to navigate these arcs effectively.	The robotic arm must be able to perform repetitive back-and-forth movements over designated areas while also executing sweeping motions to ensure thorough cleaning.	3	Executing precise movement patterns to clean specified areas and navigate curved wall surfaces effectively.
What are your priorities in terms of performance (e.g., speed, precision, durability)?	Precision and durability are the top priorities, with speed being less important; the focus should be on performing tasks accurately.	Like Rodrigo, precision and durability are essential, with a strong emphasis on avoiding damage to the tank and ensuring accuracy in operations.	The robotic arm must prioritize precision and durability in its design and operation, focusing on executing tasks accurately while preventing any potential damage to the tank.	5	Ensuring precise and durable performance during operations to maintain the integrity of the tank while achieving accurate cleaning results.
What would success look like for you in terms of this robot's arm capabilities? (What we need first)	Success for the robotic arm would be measured by its consistency in performance.	Success means completely removing identified waste from the wall and ensuring that the cleaning protocol effectively eliminates all contamination. A robust and consistent program is essential.	The robotic arm must demonstrate consistent performance and effectively remove identified waste from tank walls	4	Achieving reliable and thorough cleaning of pre-identified waste while maintaining a consistent operational performance throughout the cleaning process.
What problems is LANL/DOE currently facing that you think a robotic arm could help solve?	LANL needs to perform more detailed and finer cleaning work that larger equipment cannot reach.	The 6 DoF (degrees of freedom) robotic arms would provide the flexibility that the current equipment lacks, enabling more versatile operations.	The robotic arm must be capable of executing detailed cleaning tasks in areas inaccessible to larger equipment, utilizing its 6 DoF to offer enhanced flexibility and adaptability in operations	4	Performing detailed cleaning in confined or complex spaces where larger equipment is ineffective.

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

Appendix C: Supplemental Design Survey Questions

Table 18: 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: Codes and Standards Breakdown

Table 19: D-1 The Codes and Standards provide requirements that our team would need to follow for the safe operation of our robotic arm.

Code	Implication
Federal hazardous materials transportation law (49 U.S.C. 5103) [15]	The Secretary shall prescribe regulations for the safe transportation, including security, of hazardous material in intrastate, interstate, and foreign commerce.
Environmental Protection Agency - (40 CFR Part 191) [16]	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) [17]	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) [18]	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) [19]	Robotic System Applications - Addresses the potential use of robotic technology as it relates to different modes of plant operation
ISO 10218 [20]	Safety requirements for industrial robots

Appendix E: Requirements Checklist

Table 20: E-1 The Requirements Checklist provides examples of metrics by category to ensure that design requirements address all relevant aspects of the design's performance.

Specification Category	Examples
Geometry	size, height, breadth, length, diameter, space requirement, number, arrangement, connection, extension
Kinematics	type of motion, direction of motion, velocity, acceleration
Forces	direction of force, magnitude of force, frequency, weight, load, deformation, stiffness, elasticity, inertia forces, resonance
Energy	output, efficiency, loss, friction, ventilation, state, pressure, temperature, heating, cooling, supply, storage, capacity, conversion
Material	flow and transport materials, physical and chemical properties of the initial and final product, auxiliary materials, prescribed materials
Signals	inputs and outputs, form, display, control equipment
Safety	direct protection systems, operational and environmental safety
Ergonomics	man-machine relationship, type of operation, operating, clearness of layout, sitting comfort, lighting, shape compatibility
Production	factory limitations, maximum possible dimensions, preferred production methods, means of production, achievable quality and tolerances, wastage
Quality Control	possibilities of testing and measuring, application of special regulations and standards
Assembly	special regulations, installation, siting, foundations
Transport	limitations due to lifting gear, clearance, means of transport (height and weight), nature and conditions of dispatch
Operation	quietness, wear, special uses, marketing area, destination
Maintenance	servicing intervals (if any), inspection, exchange and repair, painting, cleaning
Costs	maximum permissible manufacturing costs, cost of tools, investment, and depreciation
Schedules	end date of development, project planning and control, delivery date

Appendix F: Calculations for QDTESM

Concept 1.

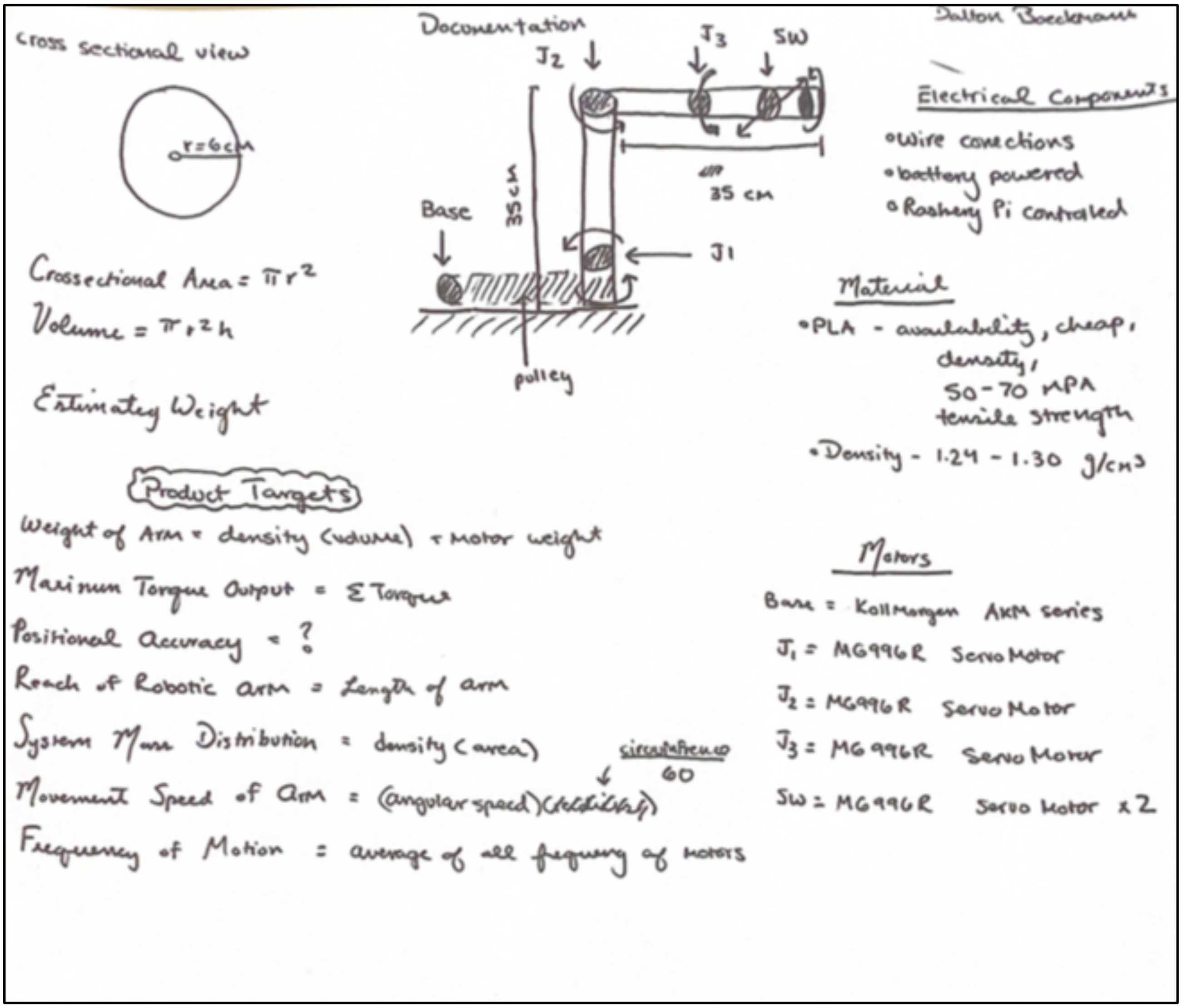


Figure 41: F -1 Concept 1 Drawing

Table 21: F-1 Material Selection for Concept 1

Material	Cost (per kg)	Density (g/cm³)	Machine Used to Print	Applicable Weight for 40 cm Arm
PETG	\$20 - \$30	1.27 - 1.40	FDM/FFF 3D Printers	Approximately 300 - 400 g
PLA	\$15 - \$25	1.24 - 1.30	FDM/FFF 3D Printers	Approximately 250 - 350 g
Nylon	\$25 - \$40	1.15	FDM/FFF 3D Printers	Approximately 200 - 300 g
ASA	\$25 - \$35	1.06	FDM/FFF 3D Printers	Approximately 250 - 350 g

Table 22: F-1 Motor Selection Concept 1

BASE MOTOR	**Kollmorgen AKM Series Servo Motor**	**Maxon EC45 Flat Motor**	**Oriental Motor PKP Series Stepper Motor**
RPS	75	80	50
Angular Speed (RPM)	4500	4800	3000
Torque (Nm)	up to 1.2	150 mNm	500 mNm
Size (dxl)(mm)	55x70	45x15	42x48
Weight (g)	500 g	95	300
COST ($)	300-500$	150-200	100- 150
Frequency	**75**	**80**	**50**
JOINT 1 -2	**MG996R Servo Motor**	**Dynamixel AX-12A**	**TowerPro MG90S**
RPS	5	3.5	5.5
Angular Speed (RPM)	60	56	90
Torque (Nm)	0.926	1.47	0.245
Size (dxl)	40x20	29x38	22x12x28
Weight (g)	55	55	13
COST ($)	14.99	49.99	7.99
Frequency	**1**	**0.9333333333**	**1.5**
JOINT 3-5	**Sg90 mini servo**	**Dynamixel Mx-28**	**MG996R Servo Motor**
RPS	**5.5**	5	5
Angular Speed (RPM)	**60**	55	60
Torque (kg-cm)	**2.5**	2.8	0.926

Size (dxl)	**22x12x28**	32x42	40x20
Weight (g)	**13**	55	55
COST ($)	**6.99**	139	14.99
Frequency	**1**	**0.9166666667**	**1**

Concept 2

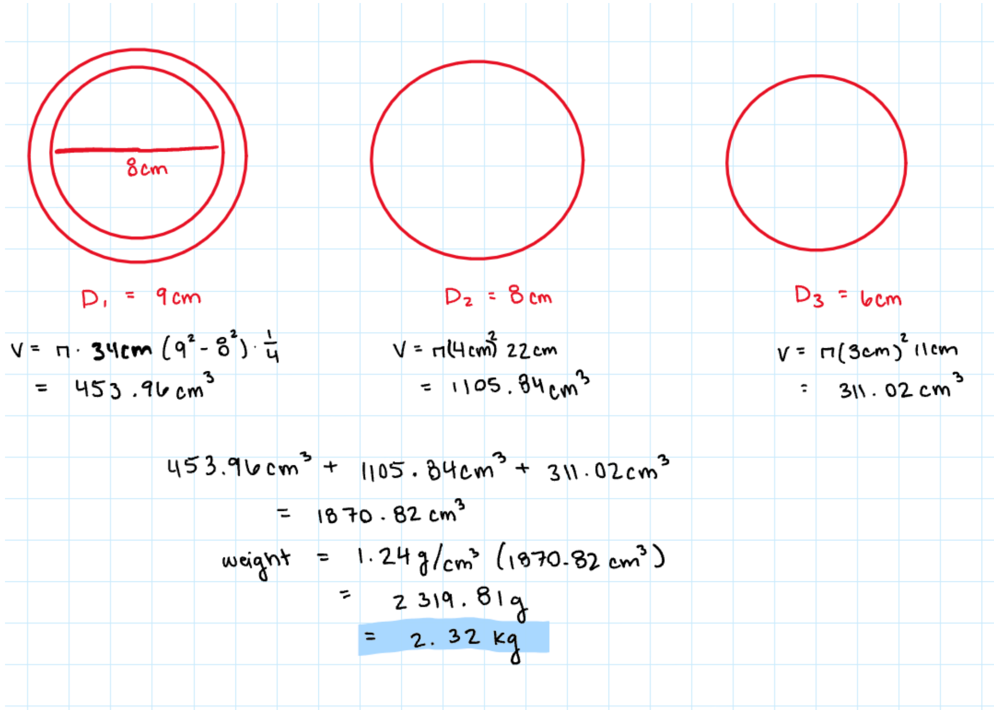


Figure 42: F-2 Concept 2 Telescoping Arm

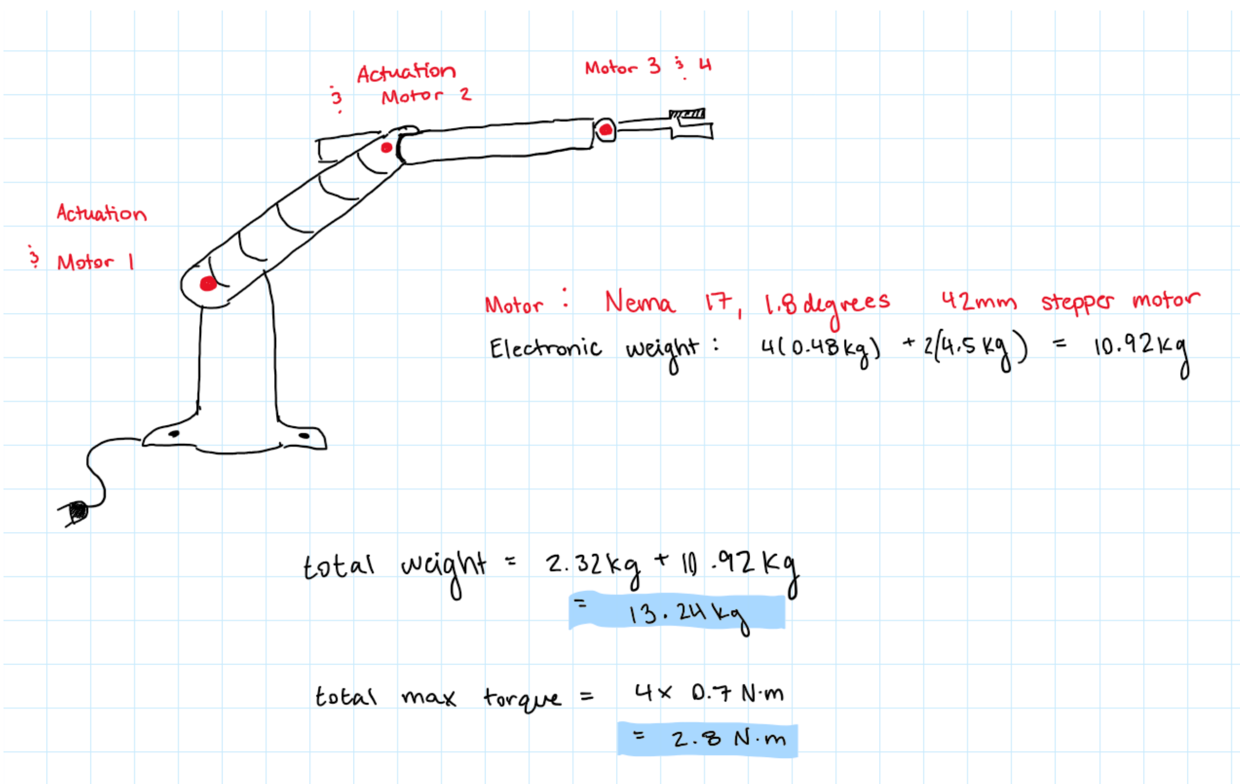


Figure 43: F-2 Concept 2 Weight

Table 23: F-2 Concept 2 Material Selection

Material	Cost (per kg)	Density (g/cm³)	Machine Used to Print	Applicable Weight for 40 cm Arm
PETG	$20 - $30	1.27 - 1.40	FDM/FFF 3D Printers	Approximately 300 - 400 g
PLA	$15 - $25	1.24 - 1.30	FDM/FFF 3D Printers	Approximately 250 - 350 g
Nylon	$25 - $40	1.15	FDM/FFF 3D Printers	Approximately 200 - 300 g
ASA	$25 - $35	1.06	FDM/FFF 3D Printers	Approximately 250 - 350 g

Table 24: F-2 Concept 2 Motor Selection

BASE MOTOR	**NEMA 17, 1.8 degrees 42mm stepper motor**	**Stepper Motor: Unipolar/Bipolar**	**NOOK Programable Linear Actuator**
RPS		200	
Angular Speed (RPM)	1500		
Torque (Nm)	0.7	0.3138	
Size (dxl)(mm)	60x42	42x48	
Weight (g)	480	350	3 kg
COST ($)	19.42	26.95	Travel Speed: 3.5 mm/s
Frequency	**25**		

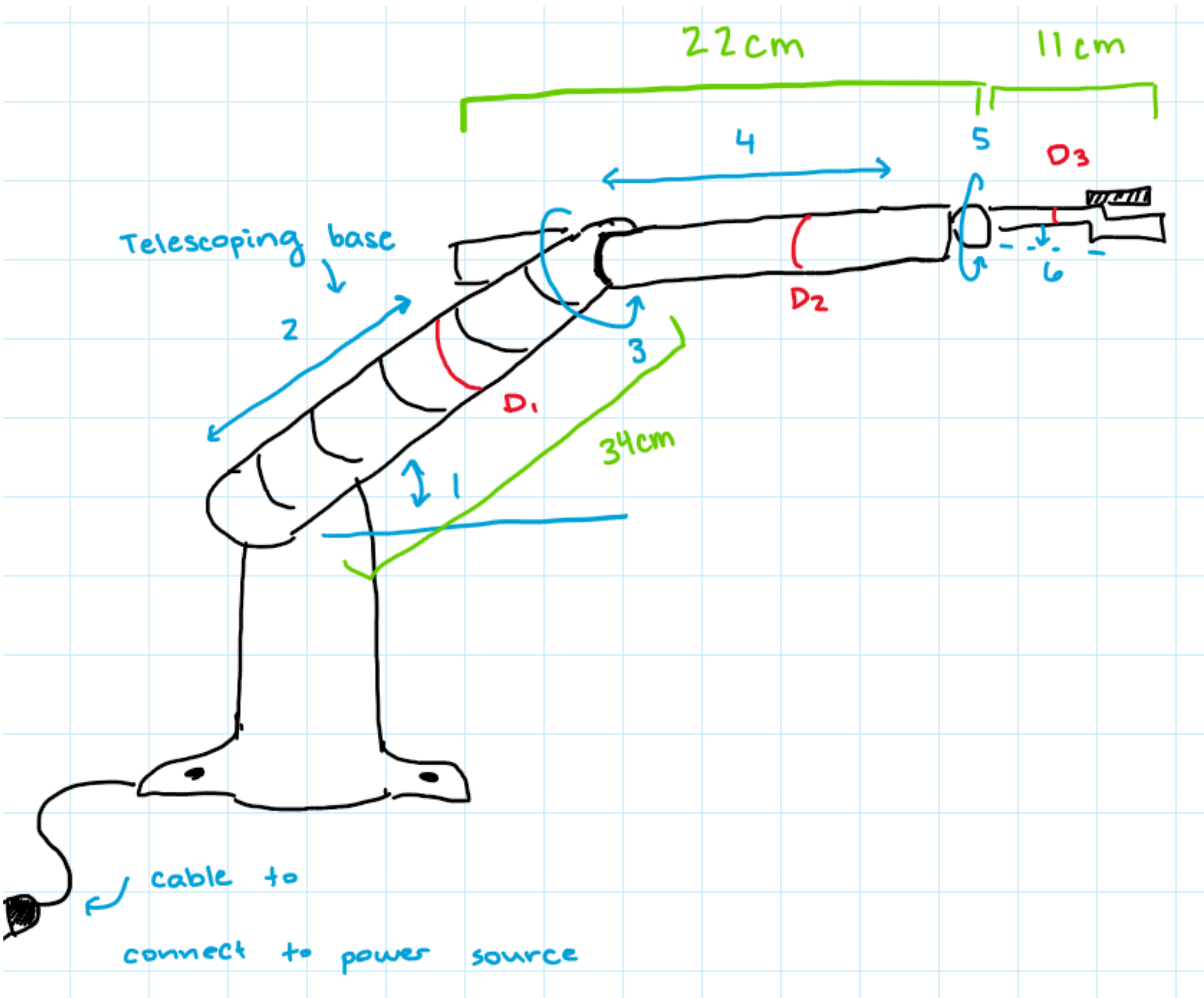


Figure 44: F-2 Concept 2 Detailed Drawing

Concept 3:

Concept 3

Specifications:

- Housing material: ABS
  - good impact and heat resistance
    - similar to aluminum and plastic
  - Density = 1.04-1.07 g/cm^3

Weight of arm / Reach of arm

Dimensions

Lengths	Diameters
Base = 100 mm	30 mm
First Linkage = 350 mm	30 mm
Second linkage = 225 mm	40 mm
Last Linkage = 170 mm	50 mm

Calculations

Volume: $V = \pi r^2 h$

Weight: $W = V\rho$

weight = (1.04)(volume) + 6 motors

$$\frac{(1.04)(\pi)(4^2)(74)}{1000} + 5.12\ \text{kg}$$

weight = 9.68 kg

First + Second linkage

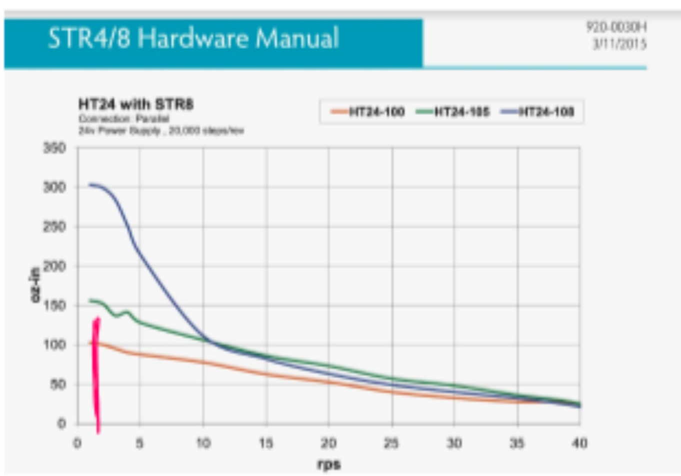
Total weight ≈ 9.08 kg

Reach = 0.74 m

Figure 45: F-3 Concept 3 Weight and Reach Length

- Motor selection
    - NEMA 24 stepper motor
    - Balances size and torque
    - 0.869 N·m
    - 6 motors minimum
        - (6 motors)(0.869 Nm) = 5.214 N·m Net torque

Frequency of Motion



Bipolar Holding Torque	0.869 N-m
Bipolar Holding Torque	123 oz-in

$f = 1 \text{ Hz}$

Figure 46: F-3 Concept 3 Motor Selection

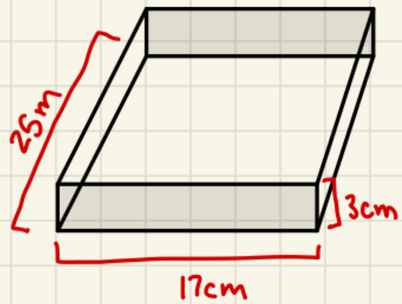
Concept 4:

Total Reach of Robotic Arm:

$$\begin{array}{r} 32.0 \\ 28.0 \\ +\ 8.0 \\ 3.0 \\ \hline 71.0\,cm \end{array} \rightarrow 0.71\,m$$

Weight of 3D-printed Parts

PLA: $1.24 - 1.30\ g/cm^3$



Base: $(25 \times 17 \times 3)\,cm^3\,(1.24)\frac{g}{cm^3}$

$= 1581\,g = 1.581\,kg$

Forearm:

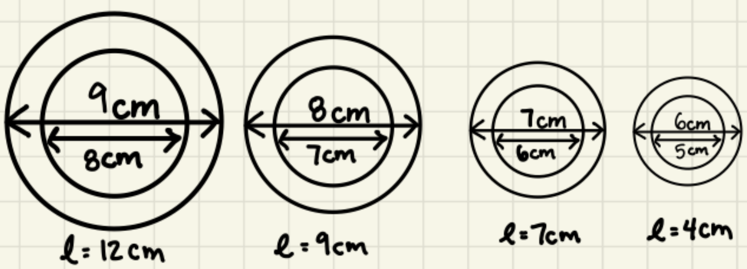
$V = \pi r^2 h$

$= \pi \left(\frac{5}{2}\right)^2 (28)\,cm^3$

$= 549.78\,cm^3\,(1.24)\frac{g}{cm^3}$

$= 681.73\,g$

$= 0.682\,kg$



Bicep

$V = \pi h (D^2 - d^2)/4$

$V_1: \pi \cdot 12 (9^2 - 8^2)/4 = 160.22\,cm^3\,(1.24)\frac{g}{cm^3} = 198.67\,g = 0.199\,kg$

$V_2: \pi \cdot 9 (8^2 - 7^2)/4 = 106.03\,cm^3\,(1.24)\frac{g}{cm^3} = 131.48\,g = 0.1315\,kg$

$V_3: \pi \cdot 7 (7^2 - 6^2)/4 = 71.47\,cm^3\,(1.24)\frac{g}{cm^3} = 88.62\,g = 0.0886\,kg$

$V_4: \pi \cdot 4 (6^2 - 5^2)/4 = 34.56\,cm^3\,(1.24)\frac{g}{cm^3} = 42.85\,g = 0.04285\,kg$

Figure 47: F-4 Concept 4 Dimensions and Weight

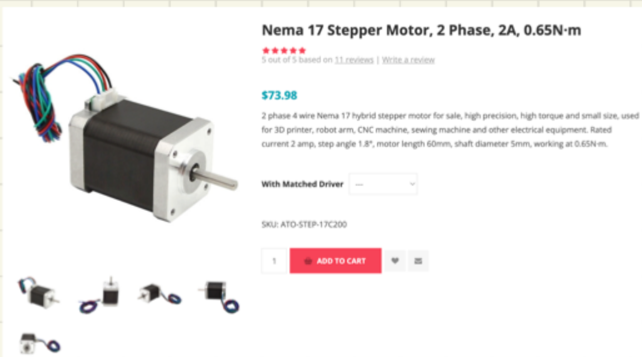
thickness : 3cm

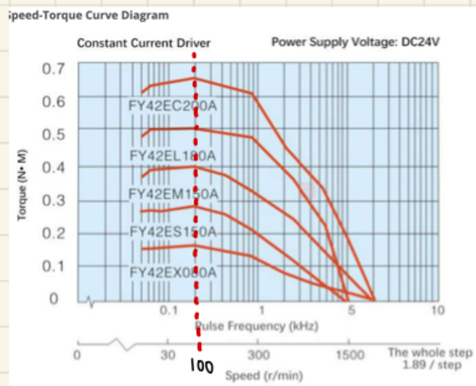
$V = 2(8\times2\times3) + (8\times6\times3)$

$= 240\,cm^3\,(1.24)\,\frac{g}{cm^3} = 297.6g = 0.2976kg$

Total plastic weight $= 1.581 + 0.682 + 0.199 + 0.1315 + 0.0886 + 0.04285 + 0.2976$

$= 3.023kg$





Physical Specification

- Model Number: ATO-FY42EC200A
- Matched the Driver Model: ATO-FYQM302A
- Flanged Size: 42 x 42mm (Nema 17)
- Motor Length: 60mm
- Shaft Diameter: 5mm
- Number of Leads: 4 wire
- Weight: 0.45kg

Robotic Total Arm Weight : 5.723kg

Maximum Net Torque Output : $6(0.65)$

$= 3.9\,N.m$

6 motors (1 for each DOF)

Weight : $0.45(6) = 2.7kg$

Frequency : $\dfrac{100\,\frac{r}{min}}{60} = 1.67Hz$

Figure 48: F-4 Concept 4 Motor Selection

[13], [14]

Appendix G: Gantt Charts for MEEN 402 Semester and Holiday Break

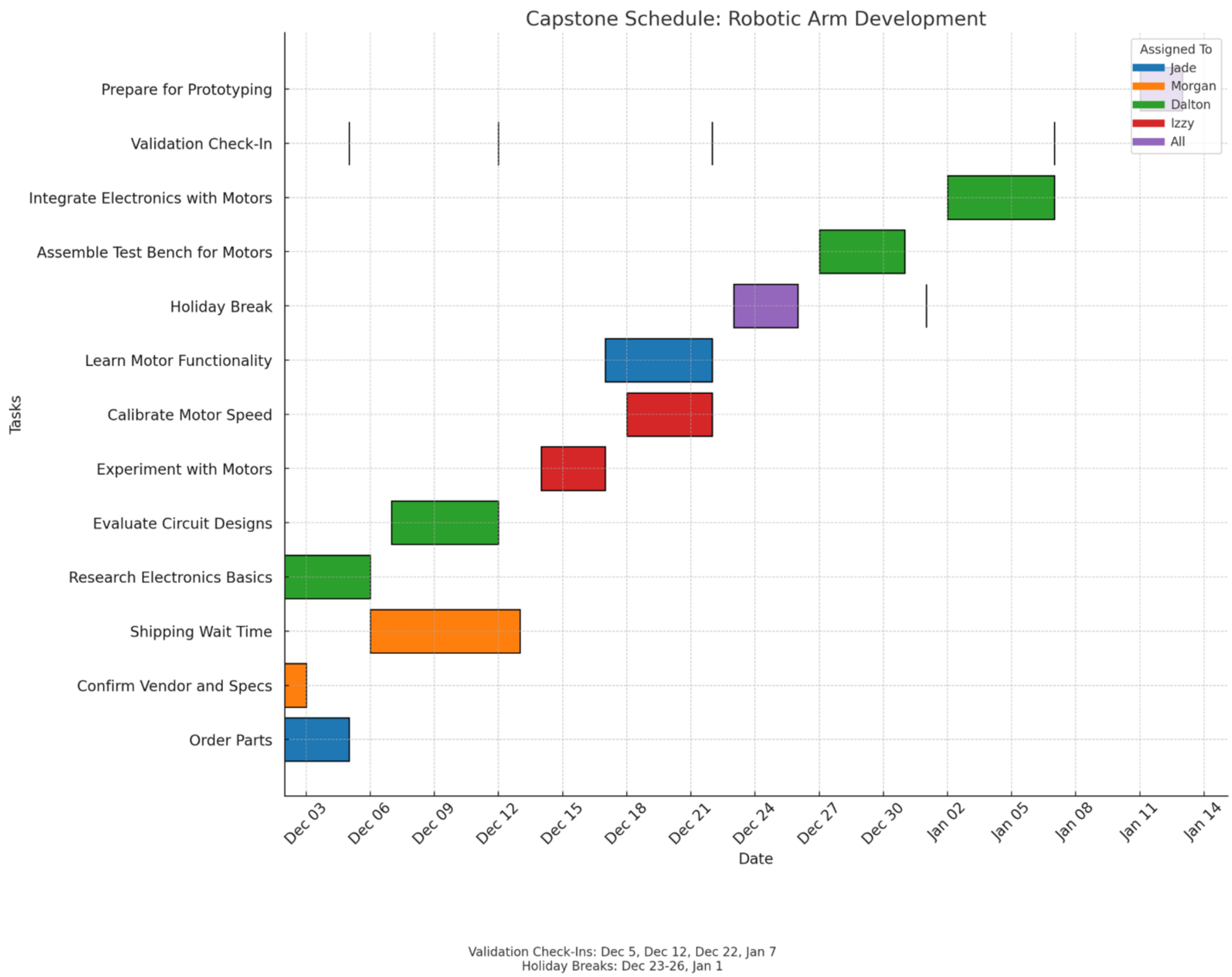


Figure 49: G-1 Gantt Chart for Holiday Break.

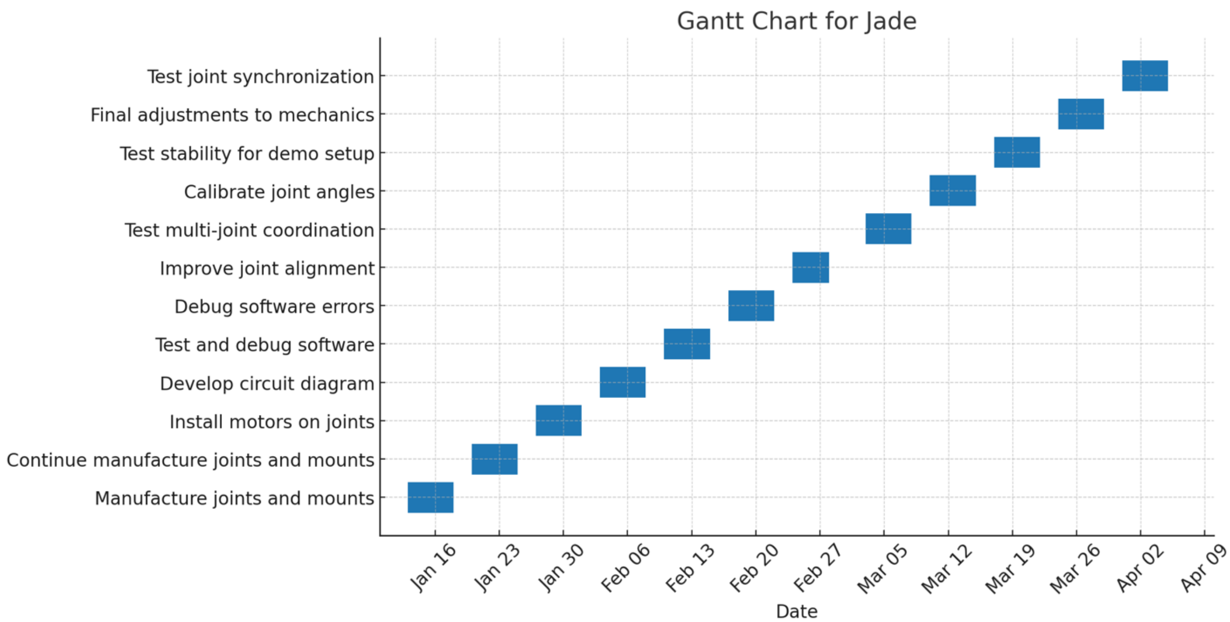


Figure 50: G-2 Gantt Chart for Jade.

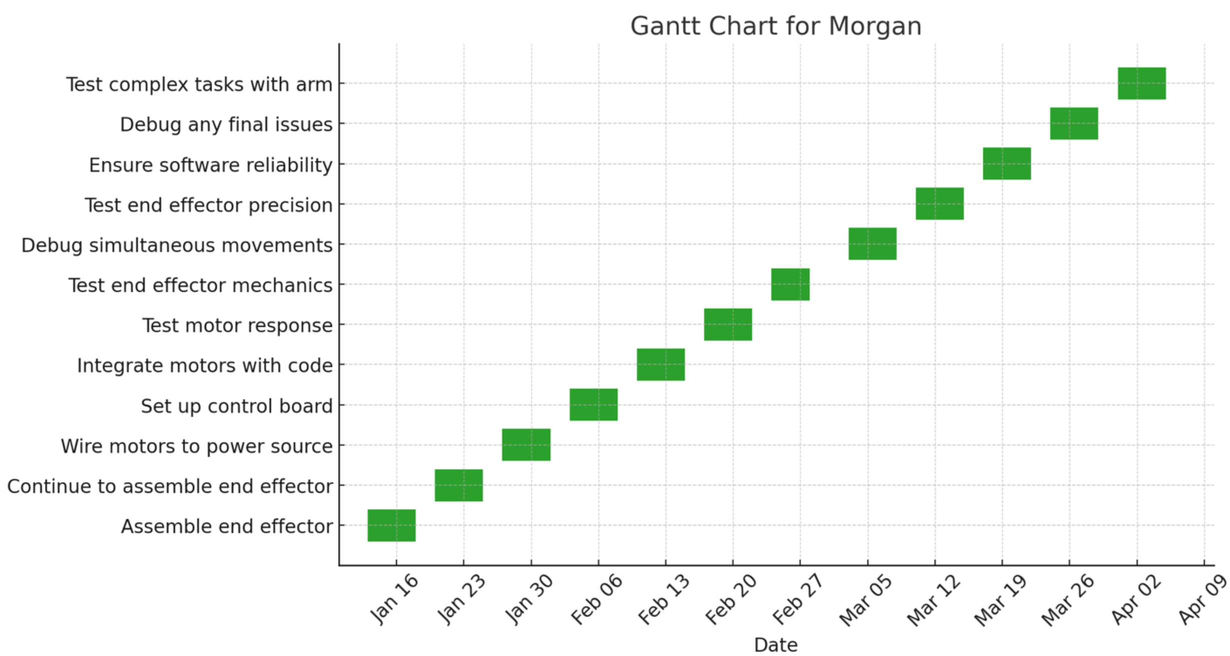


Figure 51: G-3 Gantt Chart for Morgan.

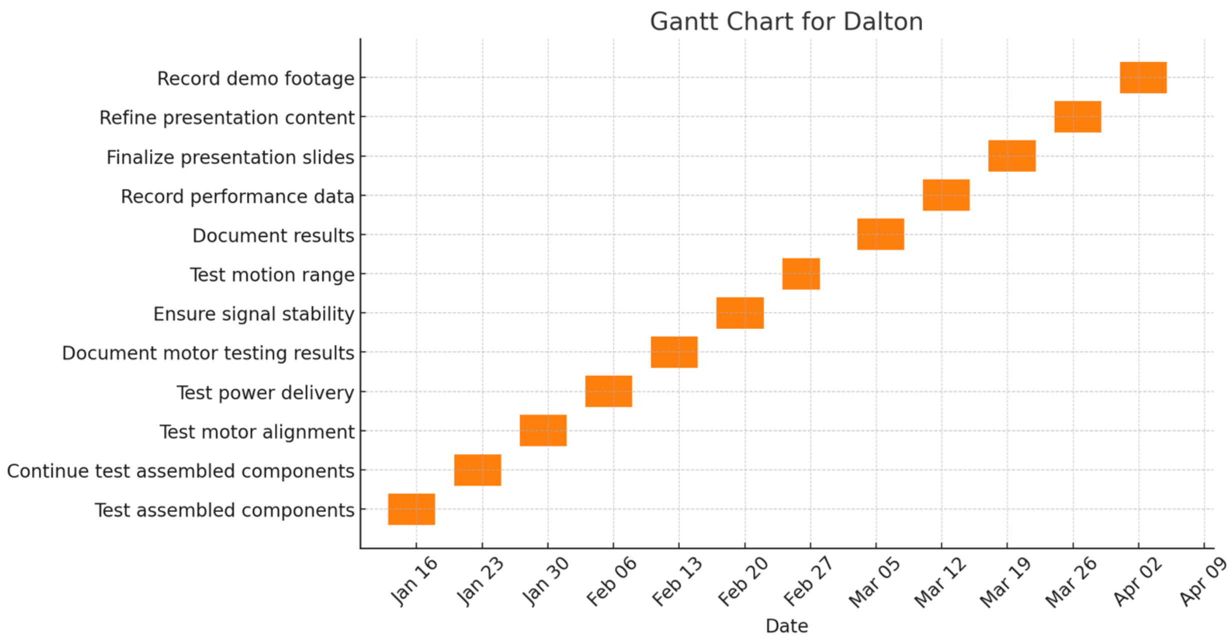


Figure 52: G-4 Gantt Chart for Dalton.

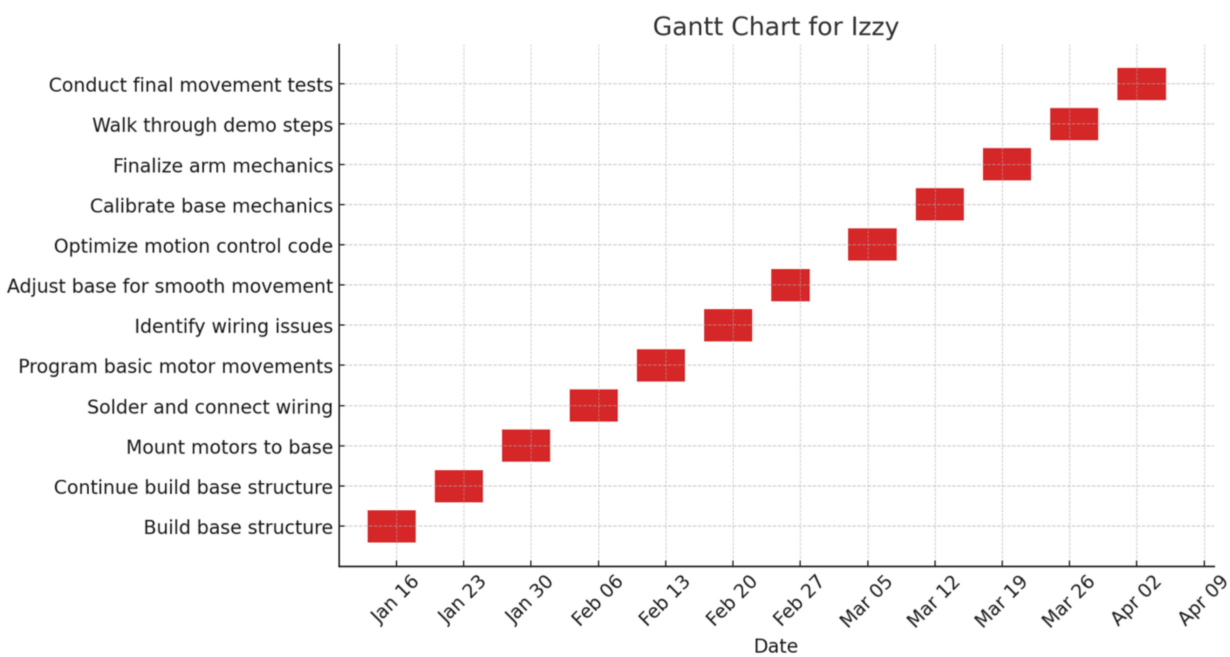


Figure 53: G-5 Gantt Chart for Izzy.

Appendix H: Risk Analysis Tables

		Risk Analysis				
Task:		Draft Detailed CAD Model				
Risk:		Parts unable to be 3D printed; Inefficient print				
Minimize Tactic:		Verify printing capabilities; Recall size ratio to set dimensions				
Consequence of Occurence	5					
	4		X			
	3					
	2					
	1					
		1	2	3	4	5
		Probability of Occurence				

Figure 54: H-1 401 Risk Analysis 1

		Risk Analysis				
Task:		Write DR3 Report				
Risk:		Procrastination; Sets team back from progress on report				
Minimize Tactic:		Delegate certain times during week to writing; Time management				
Consequence of Occurence	5					
	4					
	3					
	2				X	
	1					
		1	2	3	4	5
		Probability of Occurence				

Figure 55: H-2 401 Risk Analysis 2

		Risk Analysis				
Task:		Draft Embodiment Design				
Risk:		Custom parts unavaliable				
Minimize Tactic:		Plan for an additional off the shelf alternative				
Consequence of Occurence	5					
	4					
	3					
	2		X			
	1					
		1	2	3	4	5
		Probability of Occurence				

Figure 56: H-3 401 Risk Analysis 3

Risk Analysis

Task:	Electrical Embodiment Design Process
Risk:	Software compatibility between different electrical components
Minimize Tactic:	Plan for electrical compatability assesment

Consequence of Occurence						
	5					
	4		X			
	3					
	2					
	1					
		1	2	3	4	5
		Probability of Occurence				

Figure 57: H-4 401 Risk Analysis 4

Appendix I: Bill of Materials

ORDER #	QTY	ITEM #	DESCRIPTION	VENDOR	LINK	UNIT COST	COST
1	2	AK10-9 V2.0 KV100	Brushless DC Motor with driver board	CubeMars	ducts/ak10-9-v2-0-	$798.90	$1,597.80
2	2	AK80-6 KV100	Brushless DC Motor with driver board	CubeMars	n/products/ak80-6	$569.90	$1,139.80
3	1	GL40 KV70	Gimbal Motor with encoder	CubeMars	/products/gl40-kv7	$97.99	$97.99
4	1	Power Distribution Board	PDB Board (with XT30 pre-soldered)	Holybro	ver-distribution-bo	$8.59	$8.59
5	1	USB to CAN Connection	USB to CAN Bus Converter Base Open-Source Hardware	Amazon	kSy2yFyNNk0Z4ITr	$17.59	$17.59
6	3	2 pack XT30-M TO XT30-F	XT30-M TO XT30-F Adapter	Amazon	3NDHCuBrddW_b8	$8.99	$26.97
7	-	3D Printed Parts - PLA - or CNC	Printed through the FEDC/MEEN Department	TAMU		-	0
8	1	T-slots - M6 - Nuts (40mmx40mmx400mm)	M6 T-Nut Sliding Nut T-Slot (20 pieces)	Amazon	trusion-Profile-8m	$15.49	$15.49
9	1	T-Slots - (40mmx40mmx400mm)	4 Pack 40x40 length: 400mm	Amazon	x6W1YoM1sBSmfv	$39.50	$39.50
10	1	M6 Screws	Blue-Dyed Zinc-Plated Class 12.9 Alloy Steel (M6 x 1 mm Thread, 22 mm Long) **50 PACK**	McMaster-Carr	w.mcmaster.com/9	$11.85	$11.85
11	1	M5 Screws	Alloy Steel Socket Head Screw (Black-Oxide, M5 x 0.8 mm Thread, 10 mm Long) **100 PACK**	McMaster-Carr	w.mcmaster.com/9	$13.91	$13.91
12	1	M4 Screws (for base to Motor Connection and M4 Screws for Motor Cap Attachment to Motor)	Zinc-Flake-Coated Alloy Steel Socket Head Screw (M4 x 0.7 mm Thread, 25 mm Long) **25 PACK**	McMaster-Carr	w.mcmaster.com/9	$3.30	$3.30
13	1	M4 Screws- Bearing Fixed to Motor Cap	Blue-Dyed Zinc-Plated Alloy Steel Socket Head Screw (M4 x 0.7 mm Thread, 10 mm Long) **100 PACK**	McMaster-Carr	w.mcmaster.com/9	$14.29	$14.29
14	1	M3 Screws	Alloy Steel Socket Head Screw (Zinc Plated, M3 x 0.5 mm Thread, 10 mm Long) **50 PACK**	McMaster-Carr	w.mcmaster.com/9	$8.55	$8.55
15	1	M2.5 Screws	Zinc-Plated Alloy Steel Socket Head Screw (M2.5 x 0.45 mm Thread, 10 mm Long) **100 PACK**	McMaster-Carr	w.mcmaster.com/9	$13.95	$13.95
16	1	M2 Screws	Zinc-Plated Alloy Steel Socket Head Screw (M2 x 0.4 mm Thread, 10 mm Long) **100 PACK**	McMaster-Carr	w.mcmaster.com/9	$12.88	$12.88
17	1	Aluminum Beam	1 ft Multipurpose 6061 Aluminum Rectangular Tube	McMaster-Carr	cmaster.com/6546	$40.47	$40.47
18	1	Bearing - Crossed Roller	J1 Bearing: 80mm shaft High-Load Face-Mount Crossed-Roller Bearing	McMaster-Carr	vw.mcmaster.com/	$514.58	$514.58
19	1	Ball Bearing	J2 Bearing: 60mm shaft Ball Bearing	McMaster-Carr	ww.mcmaster.com	$46.38	$46.38
20	1	Ball Bearing	J3 Bearing: 55mm shaft Ball Bearing	McMaster-Carr	vw.mcmaster.com/	$36.12	$36.12
21	1	Ball Bearing	J4: 35mm High-Load Face-Mount Crossed-Roller Bearing	McMaster-Carr	vw.mcmaster.com/	$217.66	$217.66
22	1	Ball Bearing	J5 Bearing: 20mm shaft Ball Bearing	McMaster-Carr	vw.mcmaster.com/	$13.12	$13.12
23	1	M6 Heatset Inserts	Brass Tapered Heat-Set Inserts for Plastic (M6 x 1 mm Thread Size, 12.7 mm Installed Length) **25 PACK**	McMaster-Carr	w.mcmaster.com/9	$16.77	$16.77
24	1	M4 Heatset Inserts	Brass Tapered Heat-Set Inserts for Plastic (M4 x 0.7 mm Thread Size, 7.9 mm Installed Length) **50 PACK**	McMaster-Carr	w.mcmaster.com/9	$12.79	$12.79
25	1	M2 Heatset Inserts	Brass Tapered Heat-Set Inserts for Plastic (M2 x 0.4 mm Thread Size, 4.8 mm Installed Length) **100 PACK**	McMaster-Carr	w.mcmaster.com/9	$22.41	$22.41
						Total	$3,942.76

Figure 58: I-1 Bill of Materials