

MEEN 401 INTRO TO MECH ENGR DESIGN; SECTION 902

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DR2 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 Dennis Lee Mascarenas from Los Alamos National Laboratory, a robotic arm attachment that could contribute to solving some of the crucial cleaning needs 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 Spot robot. These spot robots will be built and designed to clean radioactive waste residues in hopes of minimizing contamination risks through less 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 demands 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. The priorities of this team include the achievement of a functional frequency around 1 Hz and the realization of both autonomous and remote control functionality to ensure versatility and dependability under various conditions.

As a guide to the development of the solution, the team performed a House of Quality ranking that has been used to rank various operational priorities such as speed, durability, precision of control, integration with Spot's movement, and dependability in various conditions. Methods like the TRIZ Matrix, design by analogy, and brainstorming techniques were used to achieve various different concepts by doing multiple rounds of brainstorming and technical evaluation. After evaluating each option, **Concept 4** showed up as the most effective balancing of weight with operating frequency in support of both maneuverability and lightweight design. The main selection criteria targeted the arm's weight, torque, positional accuracy, operational reach, and frequency of motion. All of these metrics were critical to ensure that the design meets operational demands for both the team and stakeholders.

At this stage, the team is developing the embodiment design for **Concept 4**. Given the size of the proposed manipulator relative to existing control systems, design efforts are currently centered on operational speed and weight optimization. **Figure 1** illustrates the final configuration, **Concept 4**, for the 6 DoF configuration that has met the solution space criteria outlined by the team. The design and implementation portion of this project still requires subsequent steps that the team plans to take. These steps include; a detailed validation plan where necessary for MEEN 402, project scheduling, and budgeting for prototyping and deployment. Overall, this project aims to provide an improved tool in nuclear waste management, allowing for better environmental safety and operational efficiency thanks to enhanced engineering and design.

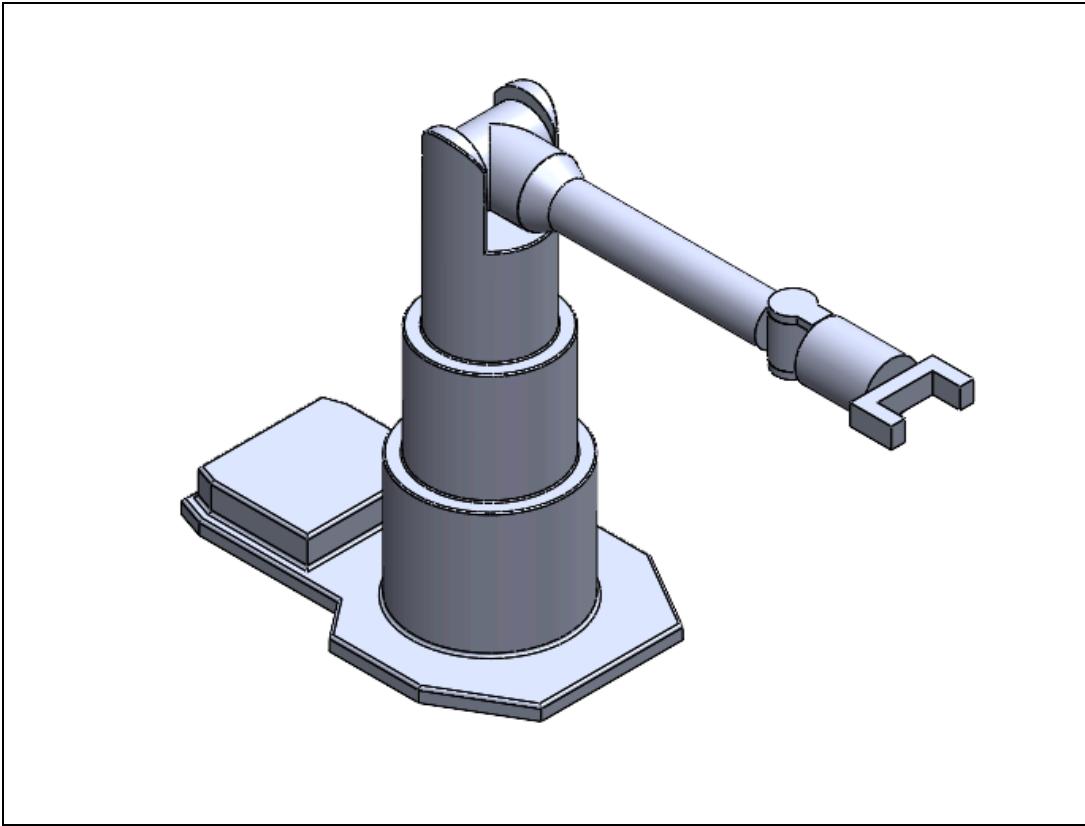


Figure 1: Preliminary Solidworks Assembly of Final Design - Concept 4

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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 conditions. The state of these tanks poses an increasing threat to both local populations and infrastructure. Through the partnership with Los Alamos National Laboratory (LANL) and Texas A&M, they have engaged a senior design team to design and fabricate a solution for this problem. The senior design team consists of four Mechanical Engineering students; Dalton Boeckmann, Isabelle Baumler, Morgan Gullo, and Jade Waldron, and is overseen by Dr. David Dennis Lee Mascarenas from LANL. In this paper, the team presents the design process for a 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 Los Alamos National Laboratory (LANL) and environmental experts, identified various challenges of removing solidified radioactive waste at the Hanford Site. LANL professionals emphasized the risks posed by waste that has crystallized over decades, highlighting that while the Department of Energy (DOE) has focused on liquid waste removal, there haven't been many advances in solidified waste removal.

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

To address these challenges, the project team identified the need for a 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.

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

In response, the project team proposes a 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 arms, their designs, and what those aspects mean about functionality. The Problem section defines how the team has set 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, 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. The main use of force-torque sensors is usually in articulated robots, which change the applied force in tasks that require delicate objects, although these sensors increase the complexity and may involve big tuning for specialized operations.

The Cobalt 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 multi-axis movement 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 that this environment and its tasks pose. These include kinematics, materials selection, control systems, and safety measures.

Kinematics, considering DoF, 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 Hartenberg 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 machine 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 have to be designed with safety features, considering the fact that they could be operated in an environment with the presence of 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 design team and customers. The mission statement can be seen clearly defined in **Table 2**. The mission statement outlines that the LANL project team will design and prototype a 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.

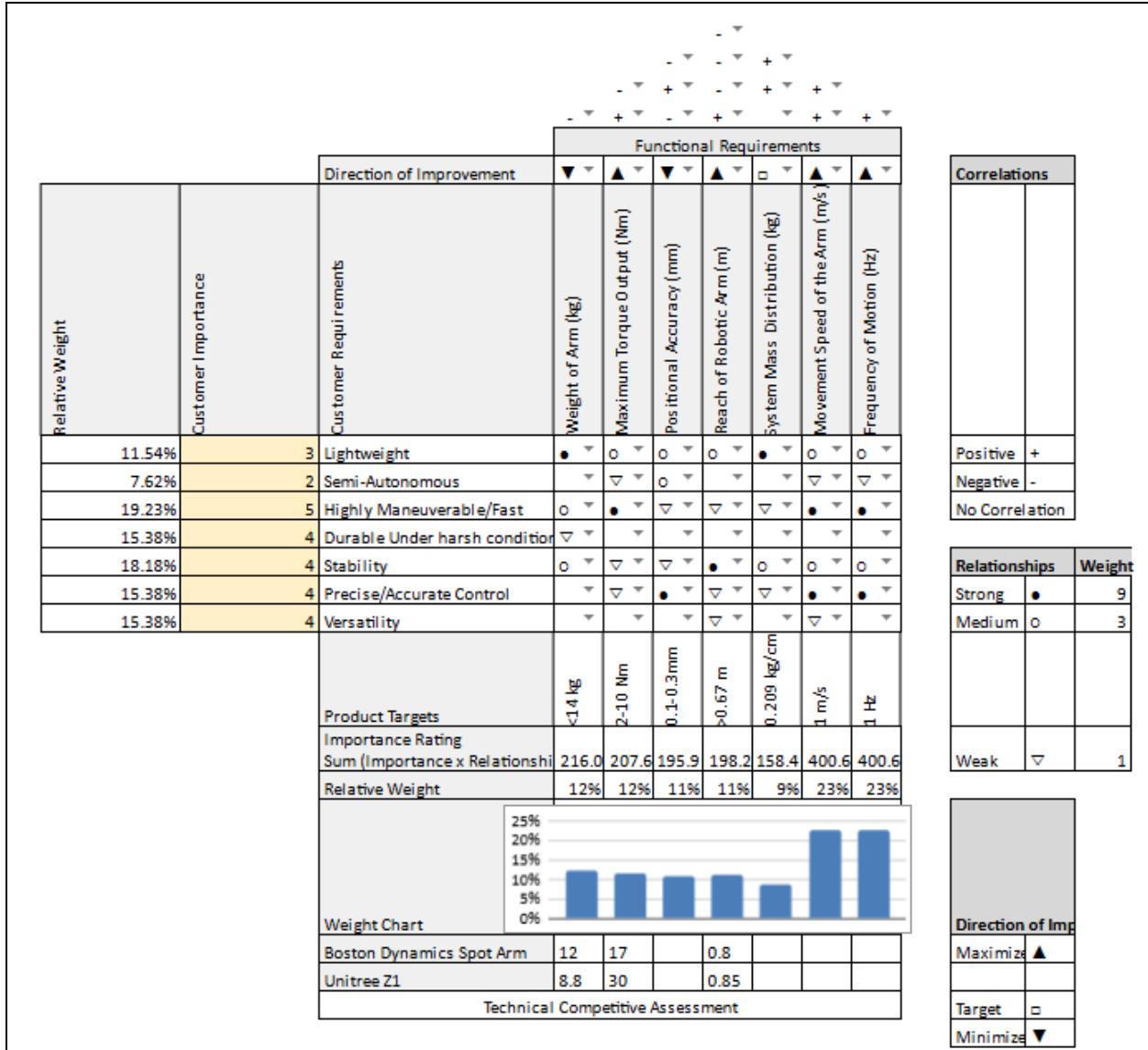


Figure 1: The HOQ relates customer needs to functional requirements, describes how the arm design compares to existing products, identifies functional conflicts, and calculates the relative weights of each functional requirement.

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.

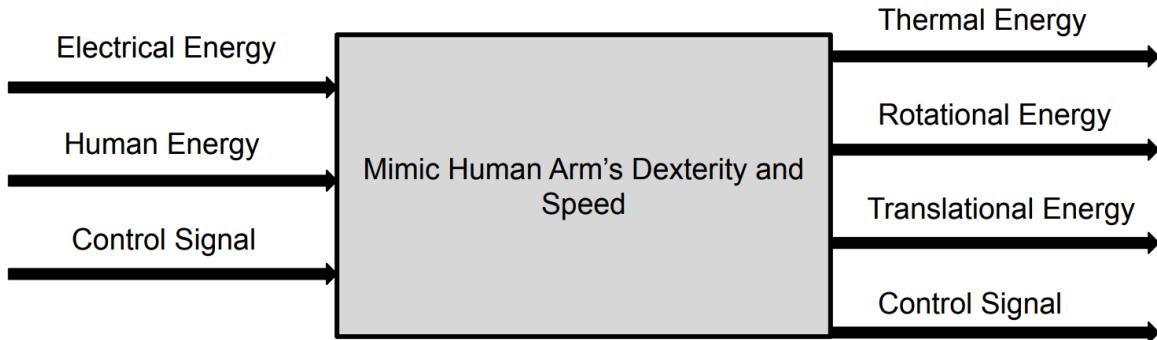


Figure 3: The black box model describes the major functional flows of our robotic arm

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**).

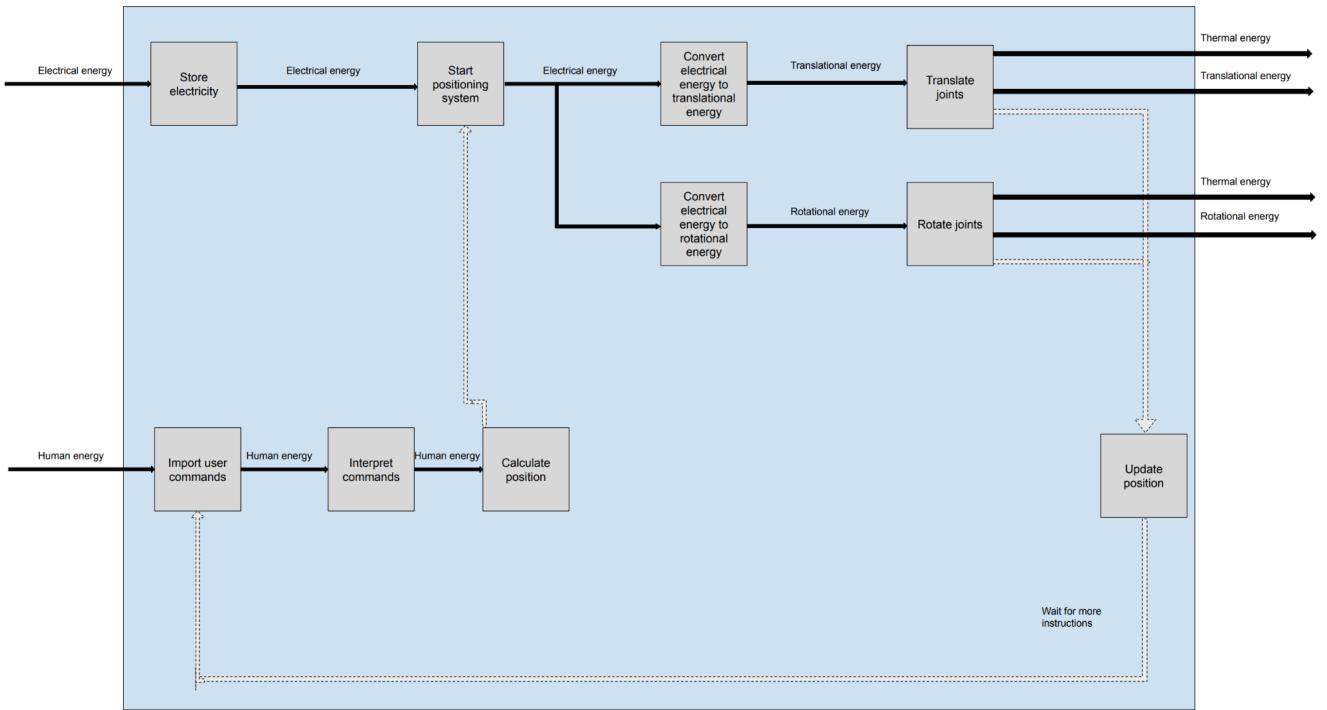


Figure 4: The full functional model describes the major flow in and out of the robotic arm system, the interactions between subfunctions allow the design to achieve the desired function

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**.

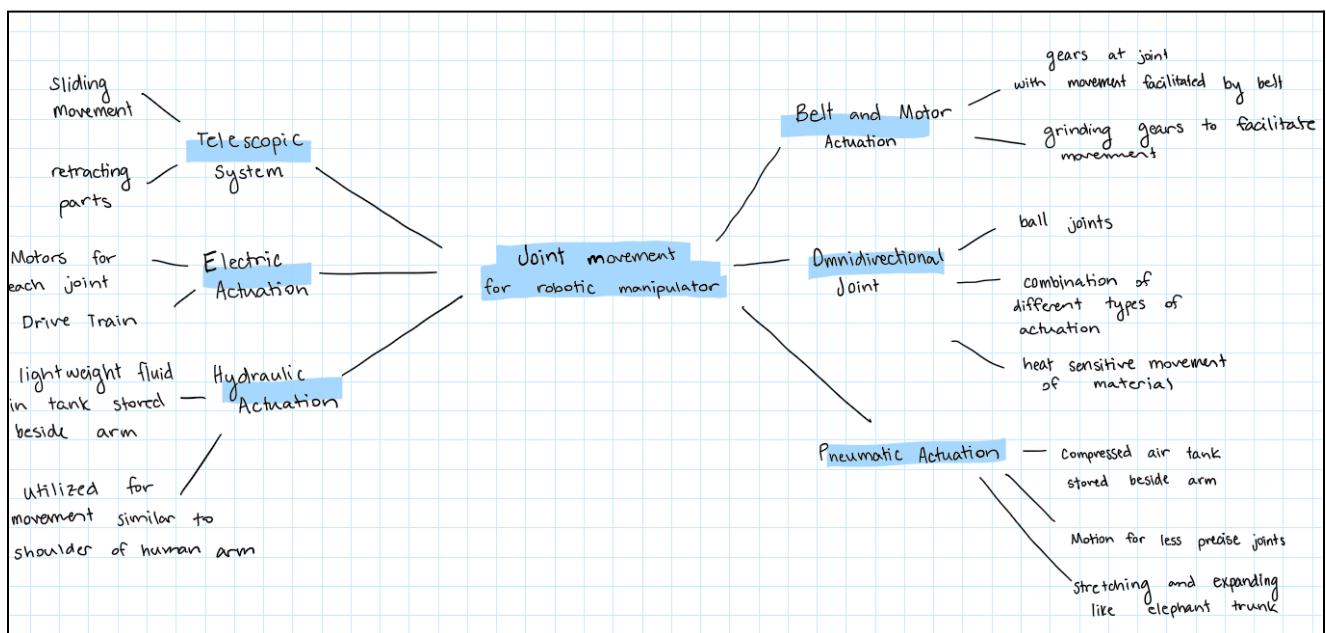


Figure 5: The joint movement systems were categorized by the type of mechanisms that would be implemented to incorporate movement.

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 6: 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, 21	36, 35, 34, 18	35, 4, 10, 14	35, 33, 33, 1	9, 18, 30, 14	19, 3, 14, 26,				
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	34, 15, 10, 14	33, 1, 18, 4	30, 14, 10, 40	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	28, 33, 17, 9	13, 27, 15	39, 3, 10, 35	35, 23		

Figure 7: 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 cross-section of this is the relevant design principles.

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].

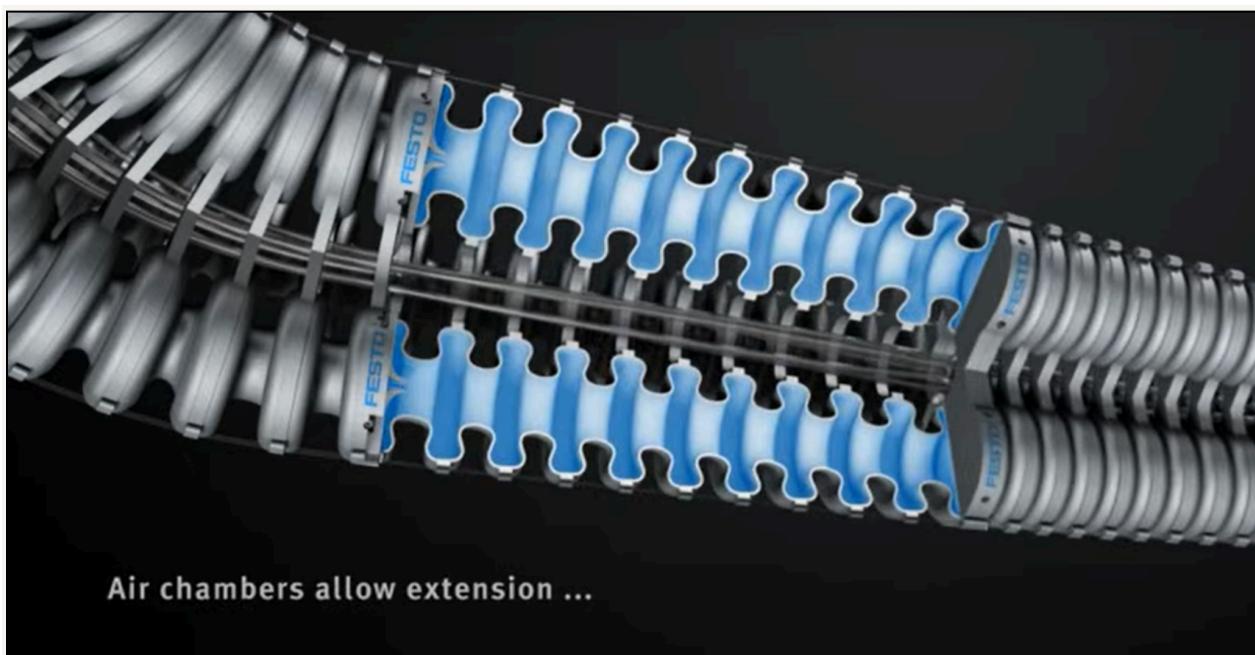


Figure 8: Bionic Handling Assistant robotic arm made up of chambers of compressed air, which allow for a wide range of motion.

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-programm ed 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.

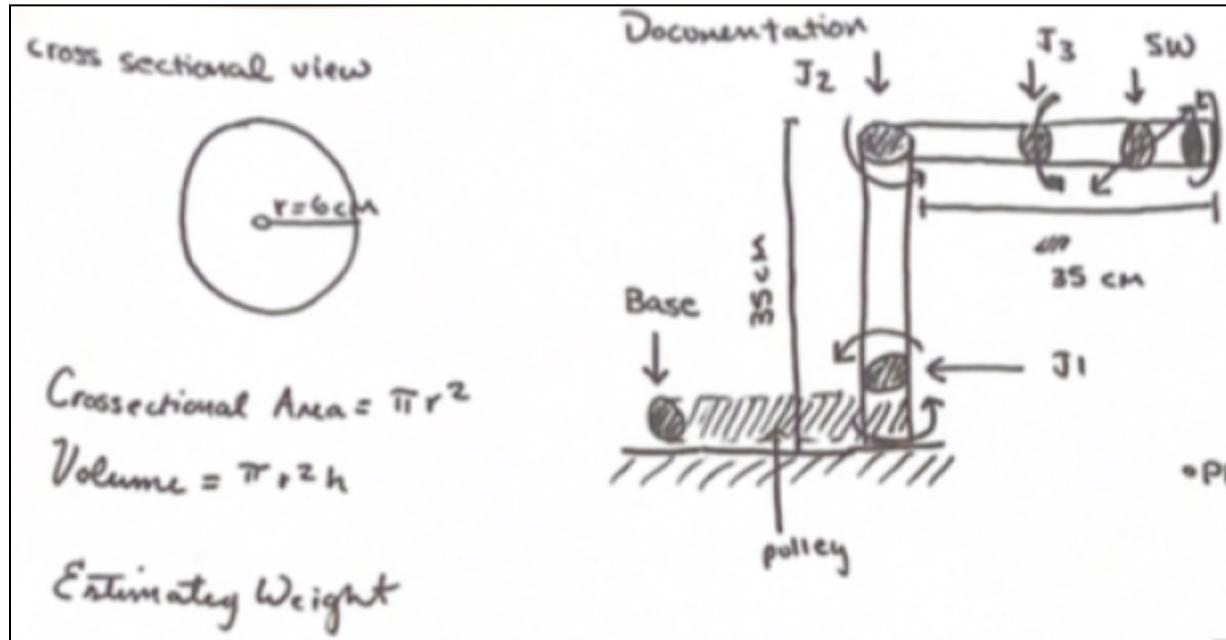


Figure 9: Concept 1 Sketch

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**.

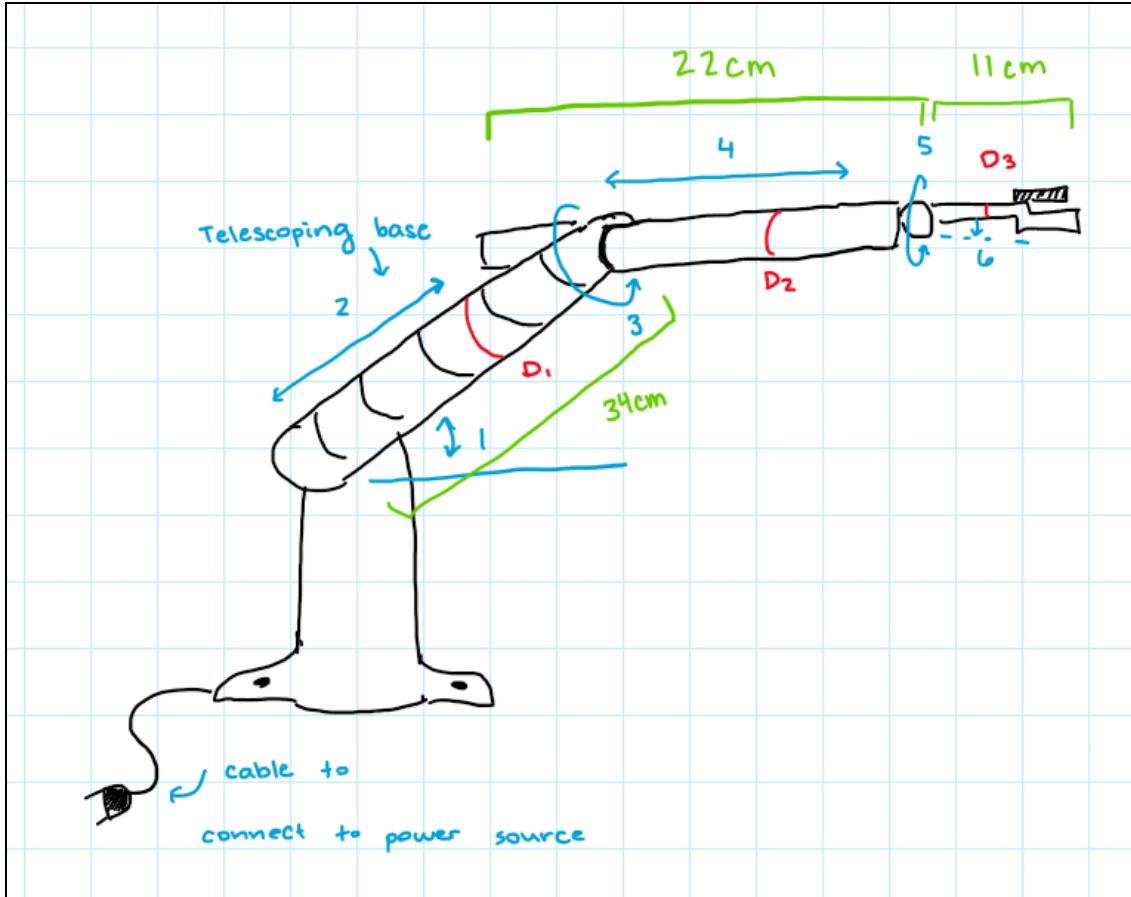


Figure 10: Concept 2 Sketch

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**.

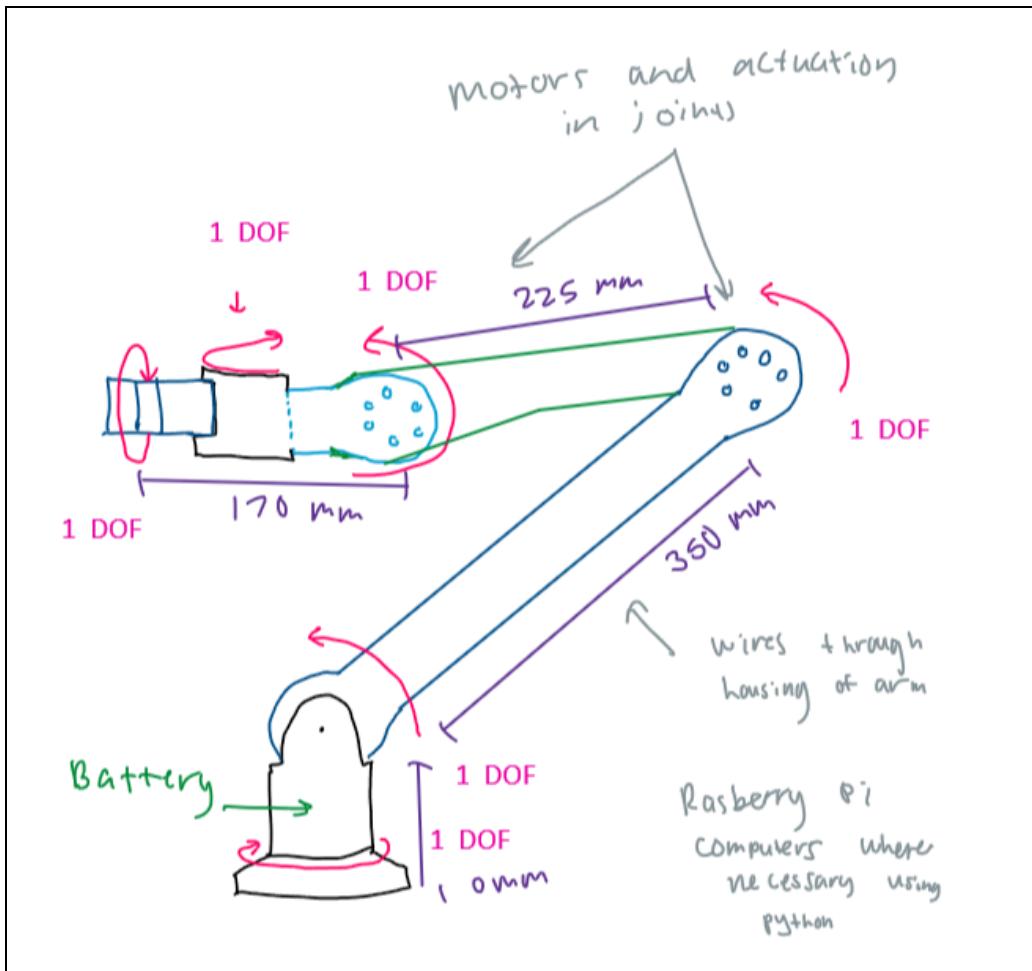


Figure 11: Concept 3 Sketch

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**.

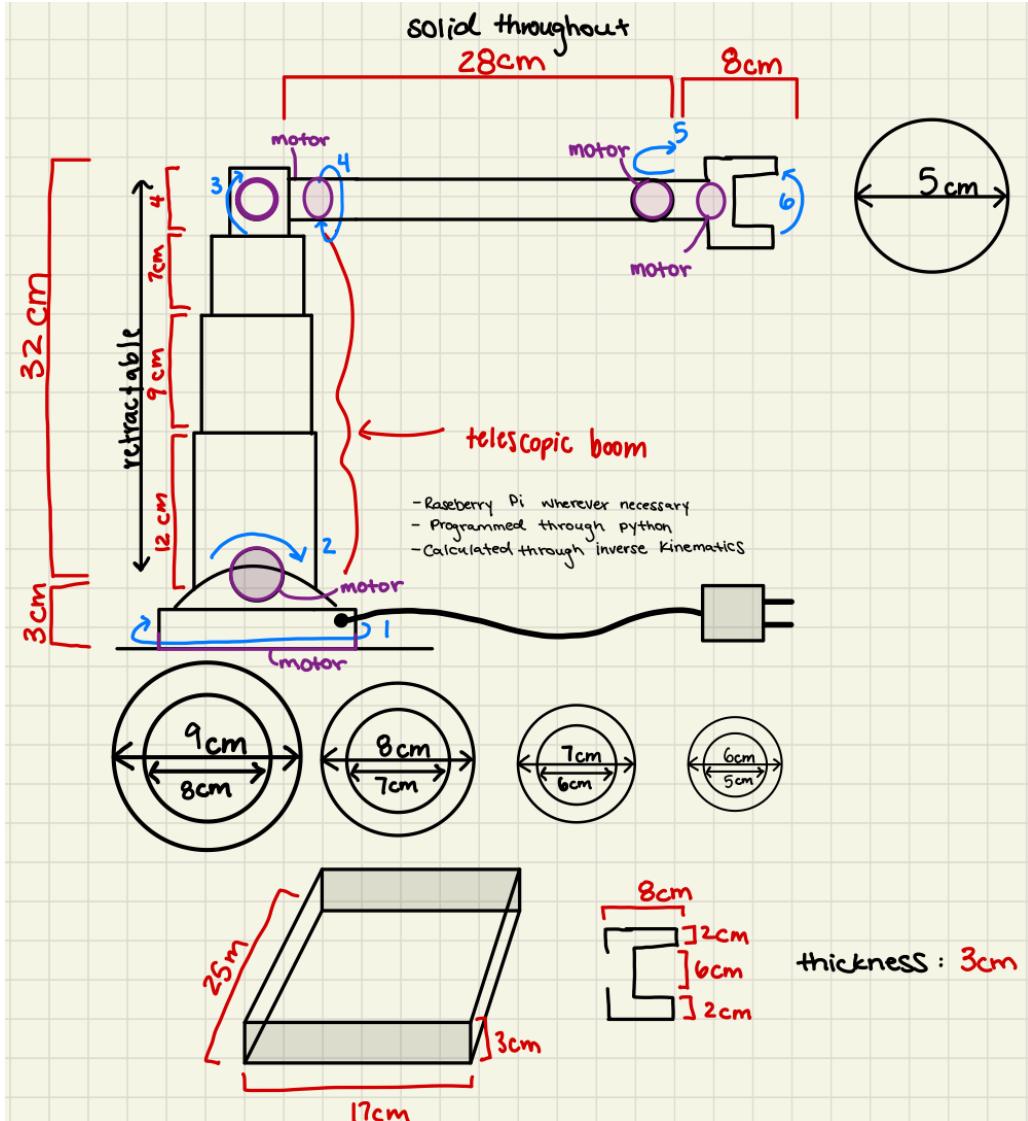


Figure 12: Concept 4 Sketch

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.

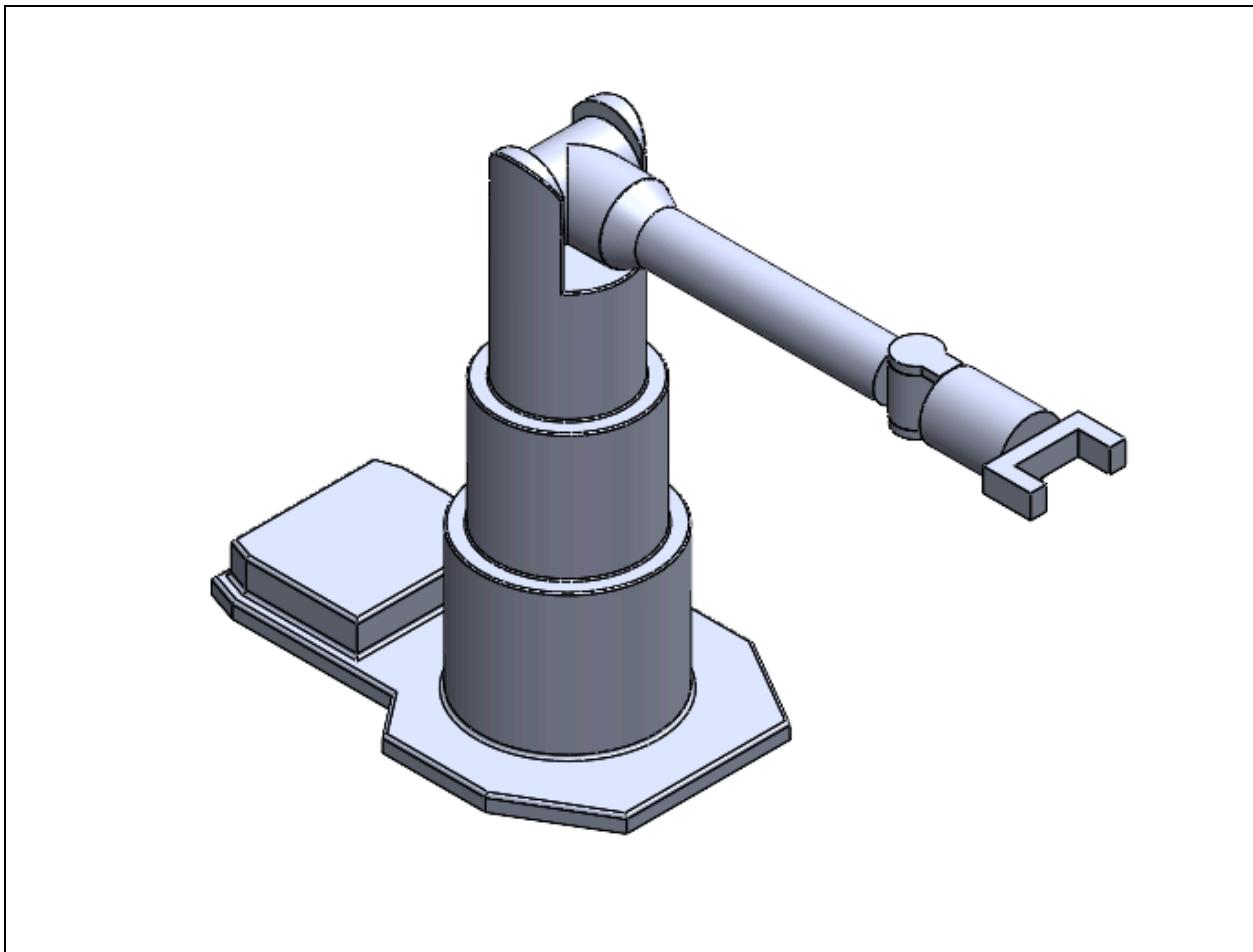


Figure 13: Preliminary SolidWorks assembly of final design concept (concept 4).

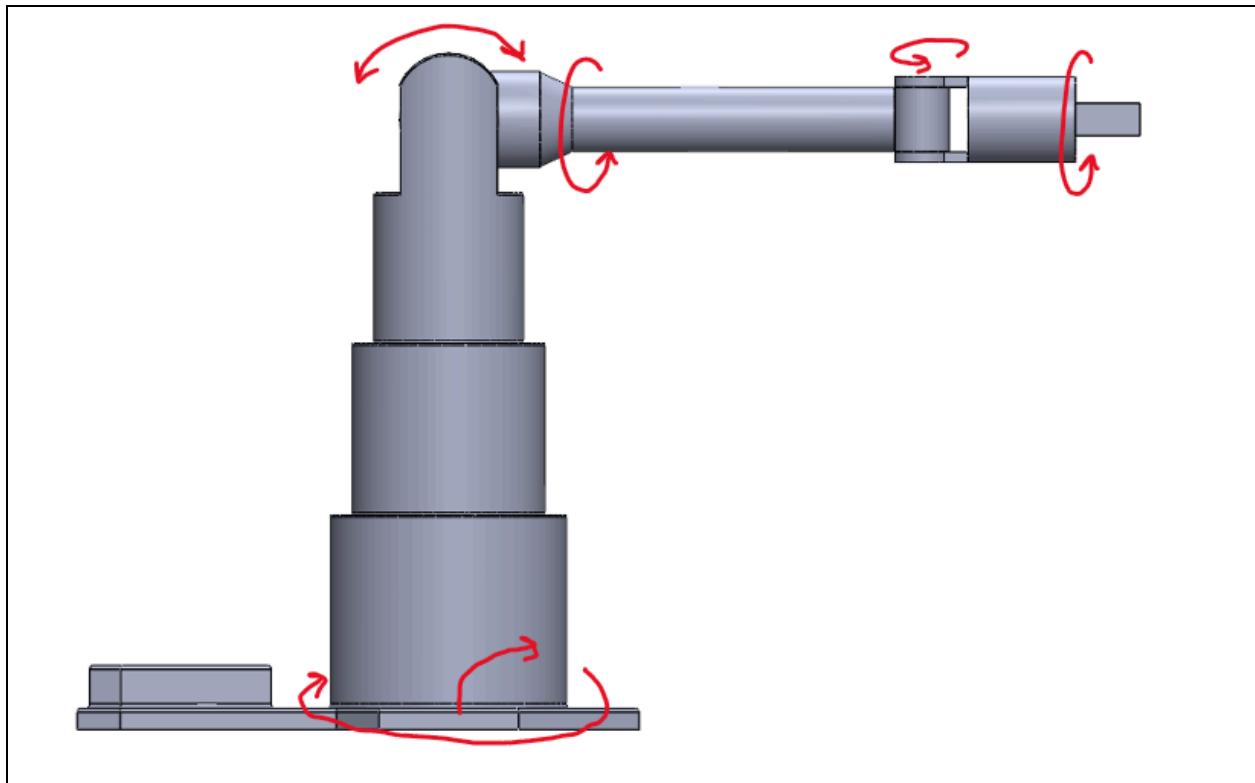


Figure 14: Preliminary SolidWorks assembly of final design concept with DoF arrows (Concept 4).

10. MEEN 401 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.

10.1 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 15**. 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.

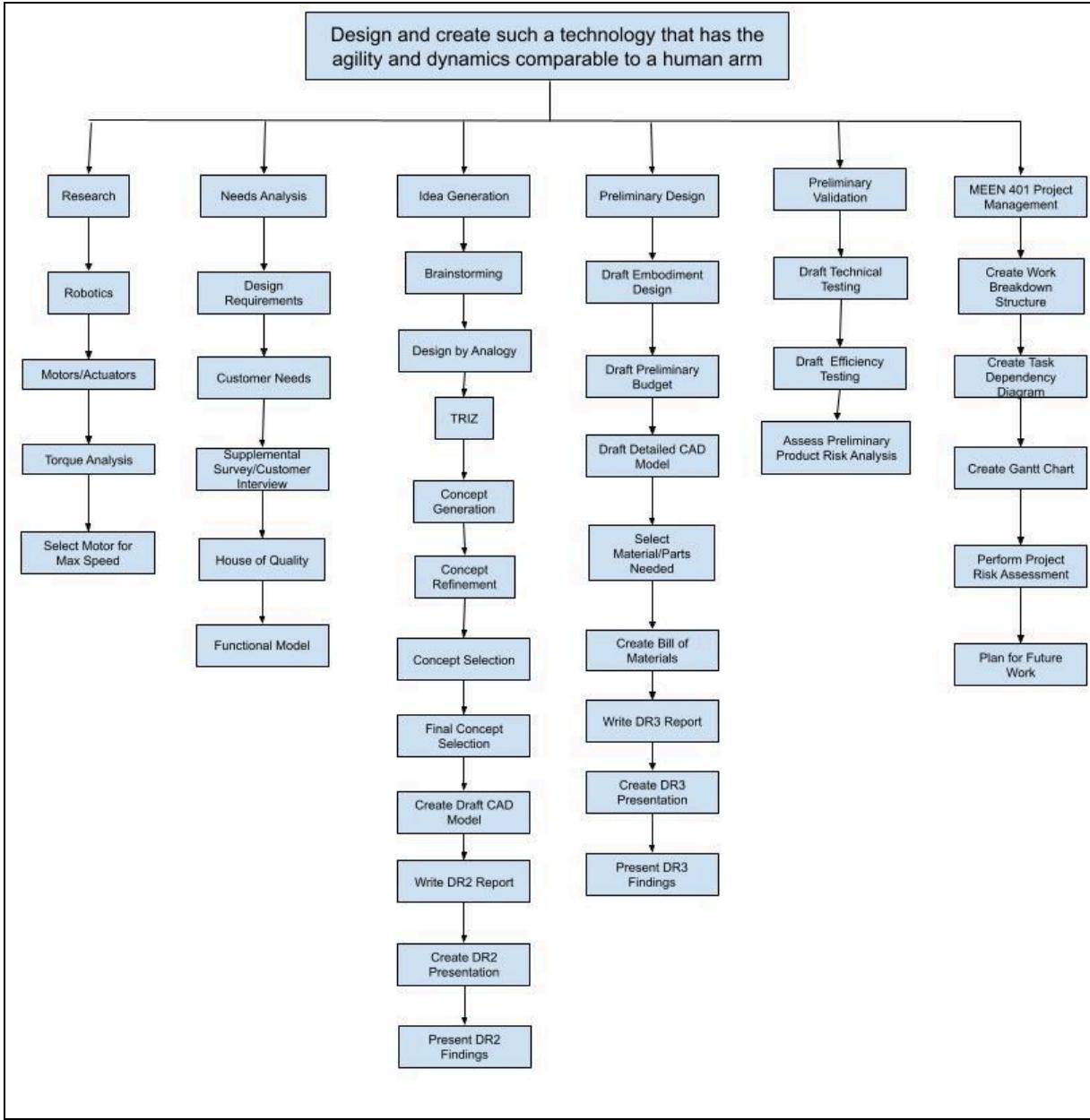


Figure 15: The WBS for the Robotic Arm Project

10.2 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 16**. 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 15** while all other tasks are shown outside of this path.

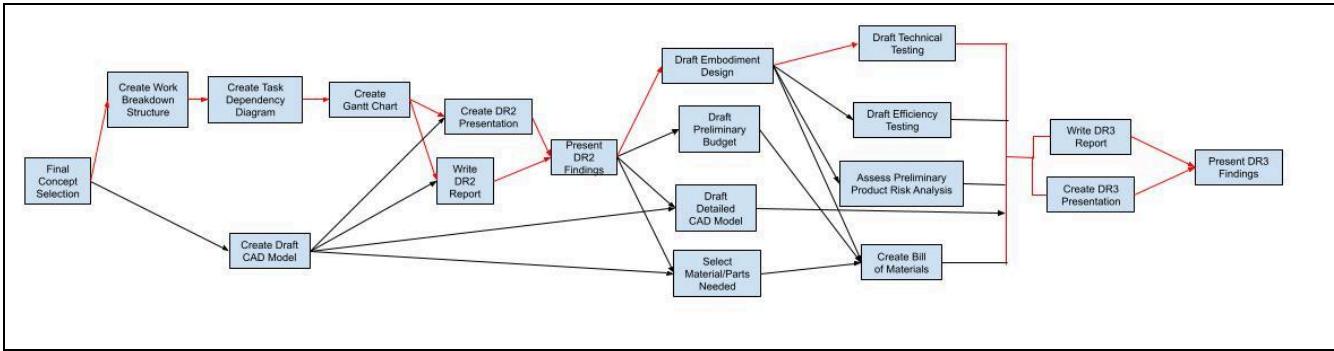


Figure 16: Task Dependency Diagram for Robotic Arm Project

10.3 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 17**. A finalized version for Spring 2025 will be included in DR3. 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.

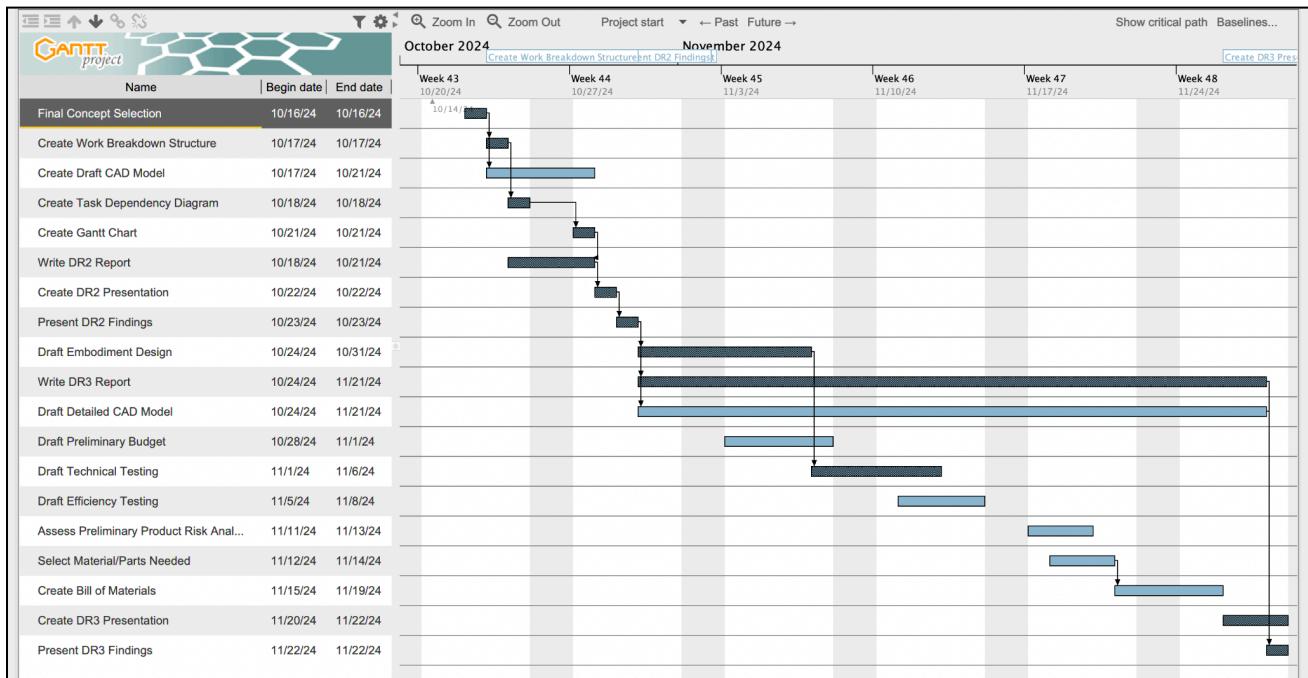
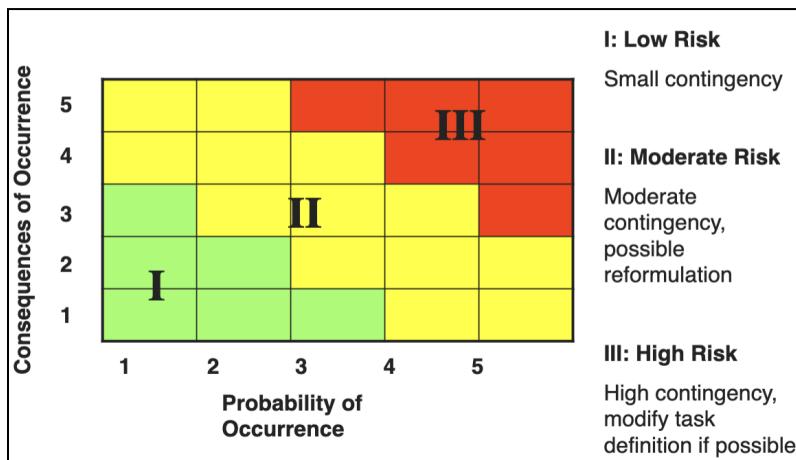


Figure 17 Gantt Chart for Fall 2024

10.4 Process Risk Assessment

To continue the project scheduling process, a risk assessment was performed for the MEEN 401 design process as detailed in **Figure 18**. 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 12**. 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 12: 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 18**. The remaining risk assessment tables can be seen in **Appendix G**.

Risk Analysis						
Task:		Draft Preliminary Budget				
Risk:		Part price change; Stock availability				
Minimize Tactic:		Draft multiple sources for part				
Consequence of Occurrence	5					
	4			X		
	3					
	2					
	1					
		1	2	3	4	5
		Probability of Occurrence				

Figure 18: Risk Analysis for Part Price Changes/Stock Availability

11. 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.

12. Future Work

After the completion of DR2, the team's efforts for the remainder of MEEN 401 will focus on drafting the embodiment design and planning for the MEEN 402 semester. The first step in the embodiment design process is determining the product architecture, which involves deciding which components will feature modular or integral designs within each subfunction. This will help define how the subfunctions interact with one another.

Next, the team will finalize the layout design, specifying the materials, geometry, and manufacturing methods, which may include 3D printing or outsourcing. A validation plan will also be developed, outlining the tests to be conducted during MEEN 402. Additionally, a preliminary budget and a bill of materials will be drafted to support planning and procurement.

A detailed CAD model will be created to provide a comprehensive digital representation of the design. To ensure efficient project management in MEEN 402, the team will develop a Gantt chart, map out all necessary deliverables, and conduct a Process Risk Assessment similar to that of MEEN 401. The final tasks of the semester will include writing DR3 and presenting the findings gathered during the report's completion.

13. 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. Future deliverables in MEEN 401 include the embodiment design for the selected concept, developing a bill of materials, and 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 A-1: Justification for the Problem Statement and Mission Statement

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

Appendix B: Customer Needs Interview Form

Table B-1: The Customer Needs Interview form 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.

<p>What kind of movements would you want to see out of an arm?</p>	<p>A robotic arm with 3 degrees of freedom (DoF) is sufficient, allowing for aiming, vertical movement, and lateral movement with depth control.</p> <p>Additional DoF may be needed for complex geometries.</p>	<p>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.</p> <p>However, he acknowledges that commercially available 6 DoF arms can better adapt to unexpected challenges and complex contours.</p>	<p>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.</p>	3	<p>Performing controlled movements in a plane with the option for more complex maneuvers.</p>
<p>How articulate would the motion have to be?</p>	<p>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.</p>	<p>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.</p>	<p>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.</p>	4	<p>Executing articulate movements to follow the contours of tank walls, transitioning between sweeping motions on flat surfaces, and navigating curves effectively.</p>

Appendix C: Supplemental Design Survey Questions

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

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

Appendix D: Codes and Standards Breakdown

Table 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 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:

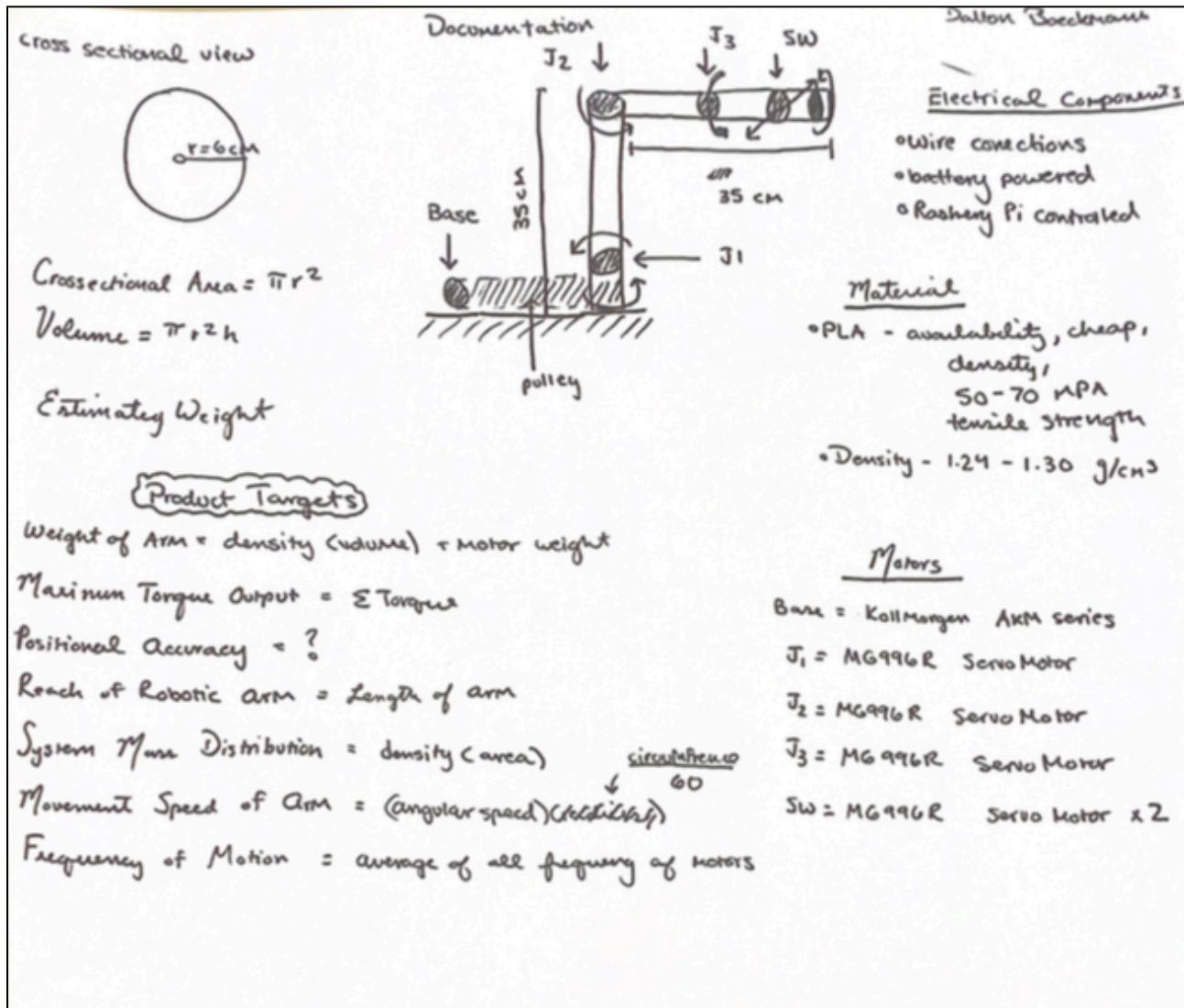


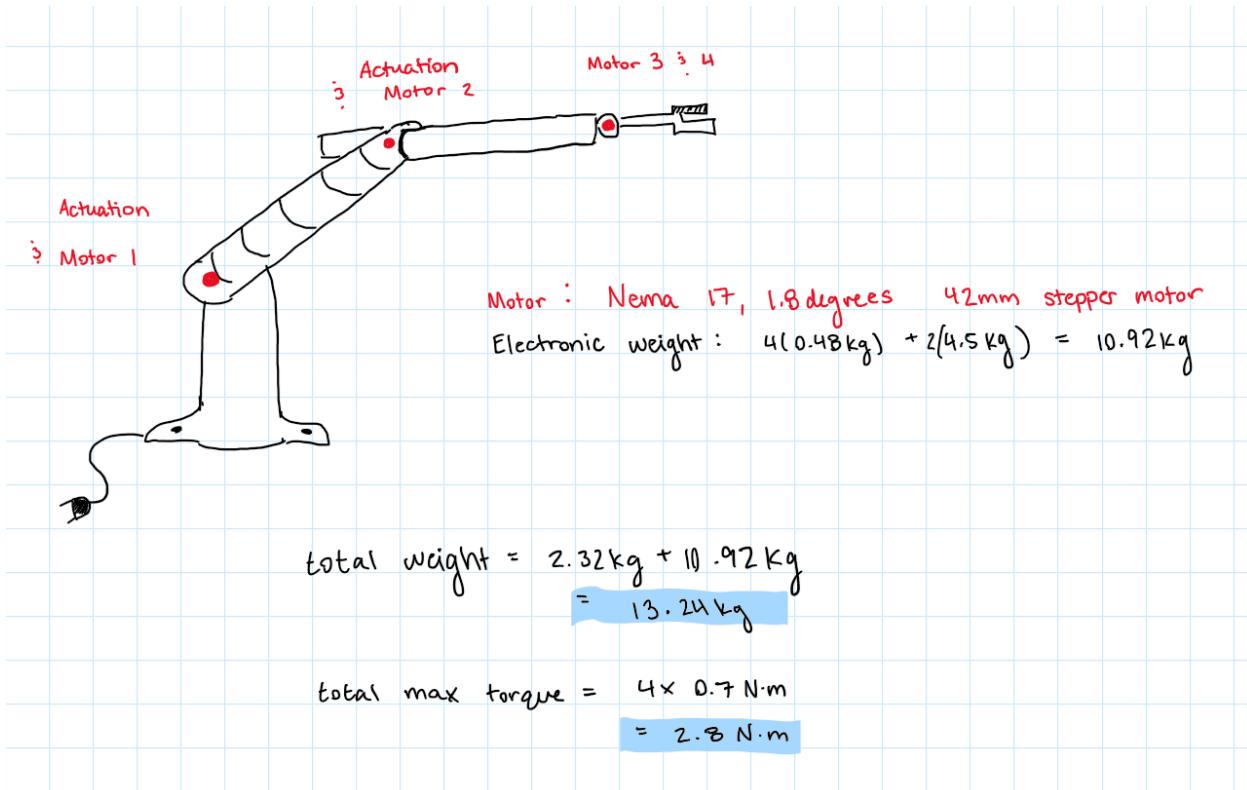
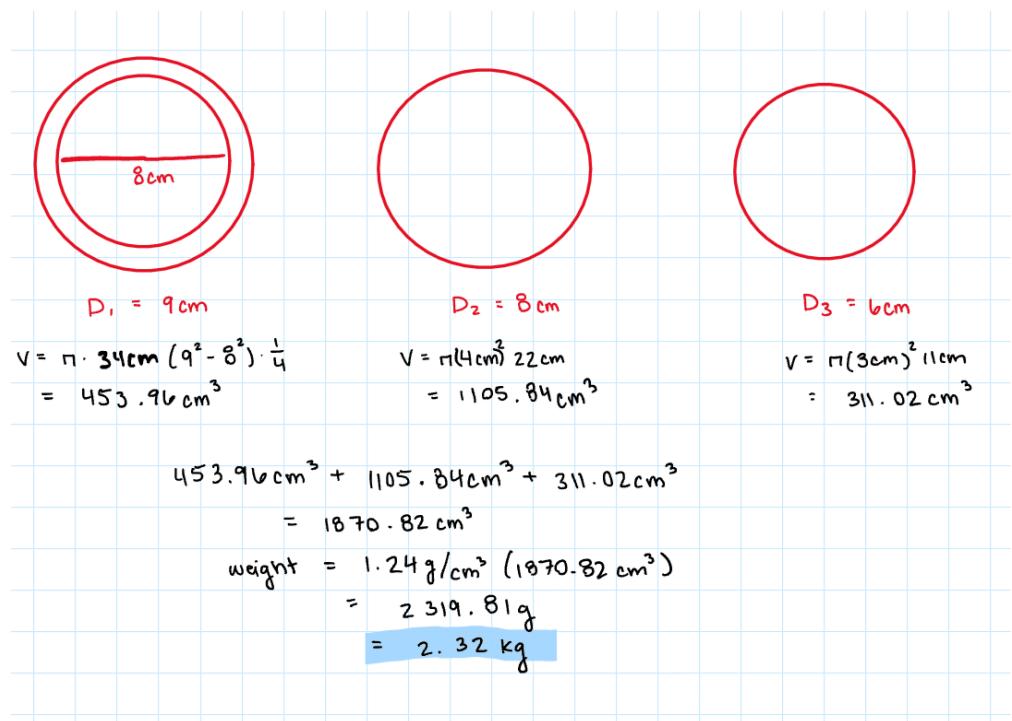
Table F-1: Material Selection for Concept 1

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 F-2: Motor Selection Concept 1

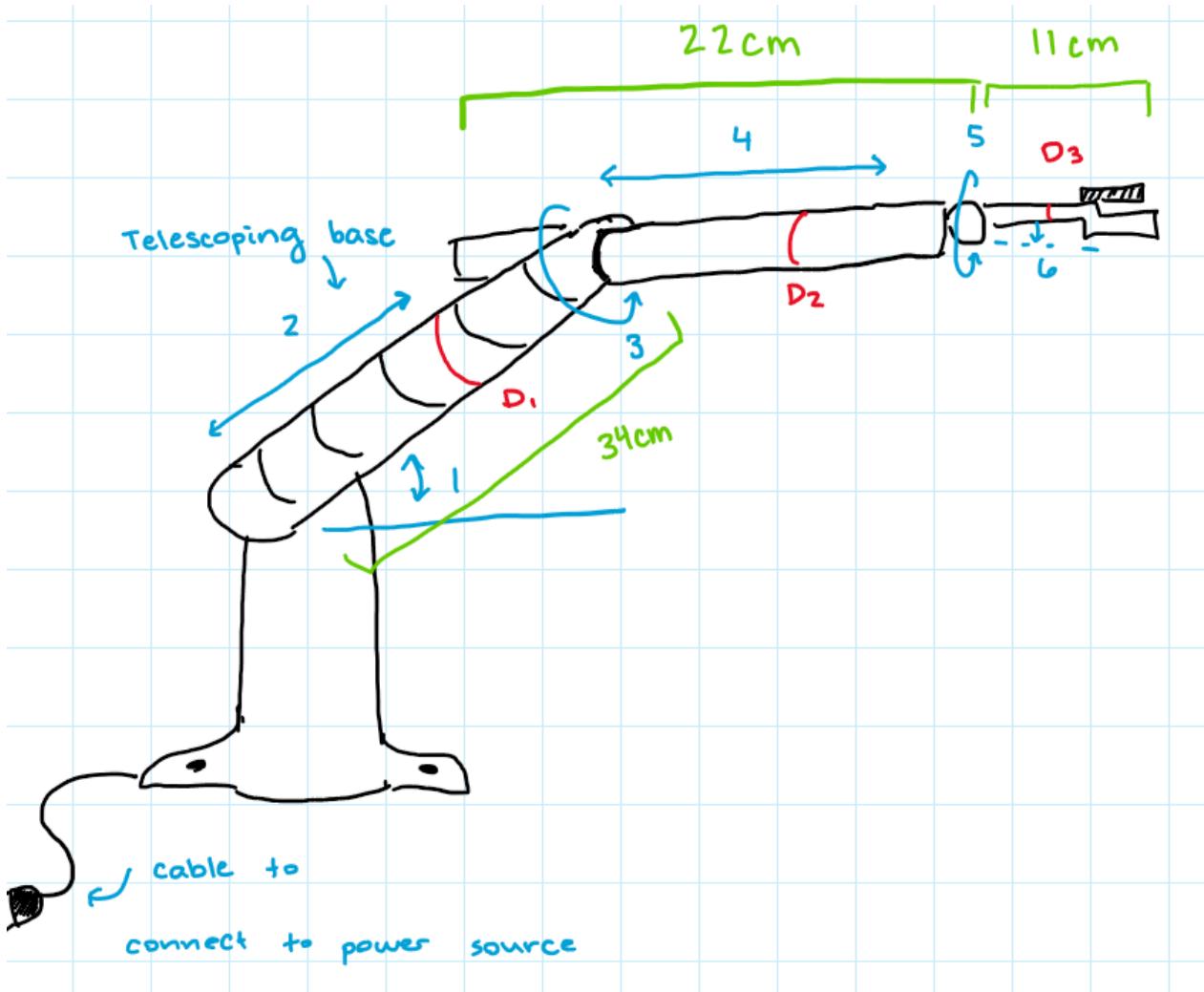
BASE MOTOR	Kollmorgen AKM Series Servo Motor	Maxon EC45 Flat Motor	Oriental Motor PKP Series Stepper Motor
RPS	75	80	50
Angular Speed (RPM)	4500	4800	3000
Torque (Nm)	up to 1.2	150 mNm	500 mNm
Size (dxl)(mm)	55x70	45x15	42x48
Weight (g)	500 g	95	300
COST (\$)	300-500\$	150-200	100- 150
Frequency	75	80	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:



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

BASE MOTOR	NEMA 17, 1.8 degrees 42mm stepper motor	Stepper Motor: Unipolar/Bipolar	NOOK Programmable 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		



Concept 3:

Concept 3

Specifications:

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

Weight of arm / Reach of arm

Dimensions

Lengths

- Base = 100 mm
- First linkage = 350 mm
- Second linkage = 225 mm
- Last linkage = 170 mm

Diameters

- 30 mm
- 30 mm
- 40 mm
- 50 mm

Calculations

$$\text{Volume: } V = \pi r^2 h$$

$$\text{Weight: } W = VP$$

$$\begin{aligned} \text{Weight} &= (1.04)(\text{volume}) + 6 \text{ MOTU} \\ &\downarrow \\ &\frac{(1.04)(\pi)(4^2)(74)}{1000} + 5.12 \text{ leg} \end{aligned}$$

$$\text{Weight} = 9.08 \text{ kg}$$

first + second
linkage
↓

$$\text{Total weight} \approx 9.08 \text{ kg}$$

$$\text{Reach} = 0.7 \text{ m}$$

Motor selection

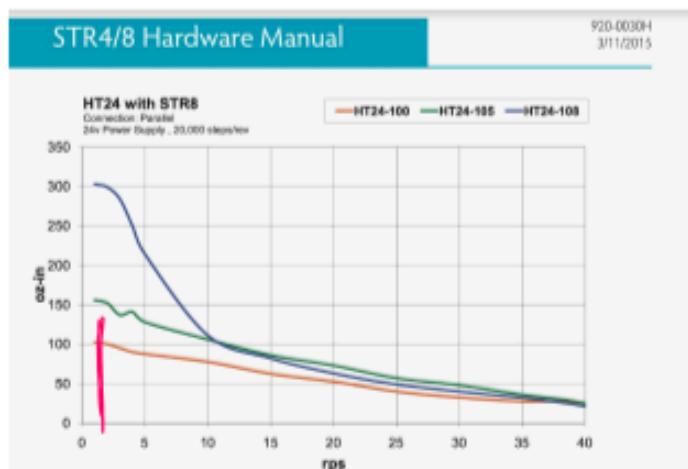
NEMA 24 Stepper Motor

- Balances size and torque
- 0.869 N·m
- 6 motors minimum

$$(6 \text{ motors})(0.869 \text{ N}\cdot\text{m}) = 5.214 \text{ N}\cdot\text{m}$$

Net torque

frequency of motion



Bipolar Holding Torque 0.869 N·m

Bipolar Holding Torque 123 oz·in

$$f = 1 \text{ Hz}$$

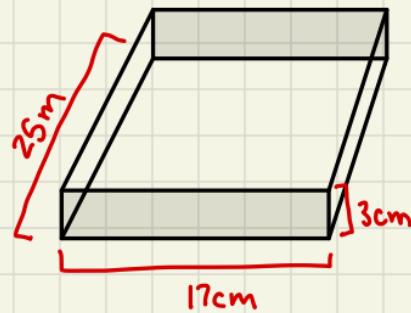
Concept 4:

Total Reach of Robotic Arm:

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

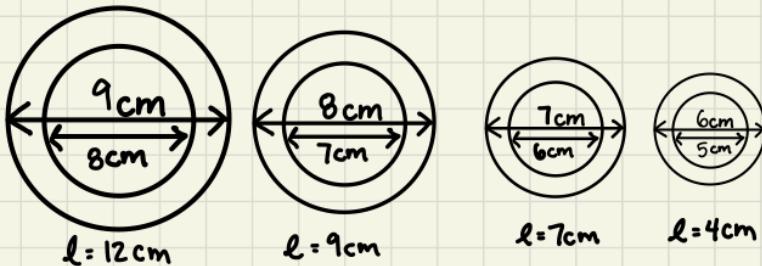
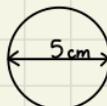
Weight of 3D-printed Parts

$$\begin{aligned}
 \text{PLA: } & 1.24 - 1.30 \text{ g/cm}^3 \\
 \text{Base: } & (25 \times 17 \times 3) \text{ cm}^3 (1.24) \frac{\text{g}}{\text{cm}^3} \\
 & = 1581 \text{ g} = 1.581 \text{ kg}
 \end{aligned}$$



Forearm:

$$\begin{aligned}
 V &= \pi r^2 h \\
 &= \pi \left(\frac{5}{2}\right)^2 (28) \text{ cm}^3 \\
 &= 549.78 \text{ cm}^3 (1.24) \frac{\text{g}}{\text{cm}^3} \\
 &= 681.73 \text{ g} \\
 &= 0.682 \text{ kg}
 \end{aligned}$$



Bicep

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

$$V_1 : \pi \cdot 12 (9^2 - 8^2) / 4 = 160.22 \text{ cm}^3 (1.24) \frac{\text{g}}{\text{cm}^3} = 193.67 \text{ g} = 0.199 \text{ kg}$$

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

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

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



$$\begin{aligned}
 V &= 2(8 \times 2 \times 3) + (8 \times 6 \times 3) \\
 &= 240 \text{ cm}^3 \left(1.24\right) \frac{9}{\text{cm}^3} = 297.6 \text{ g} = 0.2976 \text{ kg}
 \end{aligned}$$

$$\begin{aligned}
 \text{Total plastic weight} &= 1.581 + 0.682 + 0.199 + 0.1315 + 0.0886 + 0.04285 + \\
 &\quad 0.2976 \\
 &= 3.023 \text{ kg}
 \end{aligned}$$



Nema 17 Stepper Motor, 2 Phase, 2A, 0.65N·m

3 out of 5 based on 11 reviews | Write a review

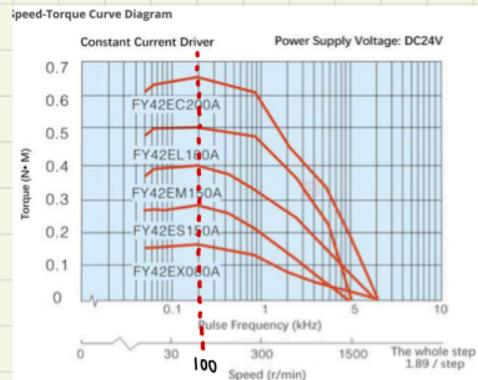
\$73.98

2 phase 4 wire Nema 17 hybrid stepper motor for sale, high precision, high torque and small size, used for 3D printer, robot arm, CNC machine, sewing machine and other electrical equipment. Rated current 2 amp, step angle 1.8°, motor length 60mm, shaft diameter 5mm, working at 0.65N·m.

With Matched Driver

SKU: ATO-STEP-17C200

1 ADD TO CART



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

6 motors (1 for each DOF)

Weight: 0.45 (6) = 2.7kg

Robotic Total Arm Weight: 5.723kg

Maximum Net Torque Output: 6(0.65)

$$= 3.9 \text{ N.m}$$

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

[13], [14]

Appendix G: 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 Occurrence	5					
	4		X			
	3					
	2					
	1					
		1	2	3	4	5
		Probability of Occurrence				

		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 Occurrence	5					
	4					
	3					
	2				X	
	1					
		1	2	3	4	5
		Probability of Occurrence				

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

		Risk Analysis				
Task:		Electrical Embodiment Design Process				
Risk:		Software compatibility between different electrical components				
Minimize Tactic:		Plan for electrical compatibility assesment				
Consequence of Occurrence	5					
	4		X			
	3					
	2					
	1					
		1	2	3	4	5
		Probability of Occurrence				